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WELDING RESEARCH

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ASSOCIATION NOTES

SUMMER SCHOOL OF WELDING, 1954

The Fourth Annual School will be held at Ashorne Hill, near Leamington Spa, from the 14 to 19 June, 1954.

Further information regarding registration, fees and programme for the School will be given in a future issue of the Journal. Members of the Association will receive full details by post, when they are available.

ANNUAL GENERAL MEETING, 16 JULY, 1953

The Eighth Annual General Meeting of the Association was held under the Chairmanship of Sir William J. Larke, K.B.E., at the Engineering Research establishment, Abington Hall. The meeting was followed by a luncheon and during the afternoon visitors had an opportunity of visiting the research laboratories.

At the luncheon, the guest speaker, Dr. H. J. Gough, C.B., M.B.E., F.R.S., proposed the toast of the Association and this was acknowledged by the Chairman of the Council, Sir Charles S. Lillicrap, K.C.B., M.B.E., on behalf of the Association. The Director then spoke on the progress of work of the Association during the past year and referred to the very satisfactory increase in membership and income.

During the afternoon the laboratories were open for inspection and showed the latest work being carried out for the engineering research programmes. The metallurgical laboratories at Park Crescent, London, were represented by a display stand in the fatigue laboratory and here was also staged a special exhibition of "Welding research and its application to industry". In this exhibition an attempt was made to show a few examples of industrial or technical developments of a practical nature arising directly from research in the Association laboratories.

The Annual Meeting was extremely well attended and a keen interest was shown by everyone in the work of the Association.

HARD-ZONE CRACK SENSITIVITY AND STRENGTH OF TWO LOW-ALLOY STEELS

Tests have been made on two-ton casts of two experimental low-alloy steels, with compositions based on those of steels giving good weldability and mechanical properties in an earlier series of tests.
The work included mechanical and weldability tests, and the effect of heat treatment at various temperatures on the mechanical properties and microstructure of the two steels was studied.

By C. L. M. COTTRELL, Ph.D., M.Sc., J. G. PURCHAS and B. J. BRADSTREET, B.Sc.

INTRODUCTION

An investigation[1] into the weldability and mechanical properties of a series of 35 experimental low-alloy (manganese-nickel-chromium-molybdenum) steels was carried out using steels made in 18 lb. high-frequency induction-furnace melts. From the results of the tests, an optimum range of composition was found, combining an 0·3 per cent. proof stress of 30 tons per sq. in., with absence of hard-zone cracking in a given Reeve weldability test, using an electrode conforming to B.S. 1719, class E 217.

It was decided to manufacture two-ton casts of two steels of selected compositions to confirm the findings of the tests on the small experimental casts. This report summarises the results of mechanical and weldability tests on these steels.

MATERIALS

The experimental steels were made in two-ton high-frequency induction-furnace melts. Each melt was cast into two one-ton ingots, and hot-rolled to plate of 1½ in., 1 in. and ½ in. thickness.

The cast analyses of the two steels are given in Table I.

Table I

Steel	C (per cent.)	Si (per cent.)	S (per cent.)	P (per cent.)	Mn (per cent.)	Ni (per cent.)	Cr (per cent.)	Mo (per cent.)
A	0·14	0·18	0·032	0·017	0·89	0·56	0·93	0·22
B	0·14	0·30	0·027	0·016	1·14	0·23	0·66	0·24

WELDABILITY TESTS

Modified Reeve weldability tests (5 in. square top plate) were made on 1½ in. thick plates from each steel. The tests were made using 4, 6, 8 and 10 s.w.g. electrodes, conforming to B.S. 1719, class E 217, and the procedure used was similar to that described earlier,[1] except that a deposition of 1½ in. of electrode per 1 in. of weld was used for all the test welds, and the anchor welds were made with 4 s.w.g. electrodes. The average welding currents used were 320, 215, 180, 135 amps. for 4, 6, 8 and 10 s.w.g. electrodes respectively.

The results of the tests, together with the welding conditions are given in Table II.

Hard-zone cracking occurred in both steels when welded with 8 and 10 s.w.g. electrodes, but with 4 and 6 s.w.g. electrodes no cracking was observed.

There was evidence of high-temperature micro-cracking in the weld metal in some of the welds. This cracking was

Table II.—Reeve Weldability Test Results (1½ in. thick plate).

Steel Ref.	Electrode Size (s.w.g.)	Average Leg Length (in.)	Hardness (D.P.N.)		Average Cracking (per cent. leg length)
			Average Peak (heat-affected zone)	Average Plate	
A	4	0·39	374	189	Nil
	6	0·31	388		Nil
	8	0·25	388		6
	10	0·20	417		10
B	4	0·37	411	213	Nil
	6	0·29	422		Nil
	8	0·24	428		7
	10	0·20	423		4

mainly associated with the root of the weld, and traces of oxide were observed in some of the cracks by examination at high magnification. The cracking was probably due to the high cooling rate and severe stress imposed when welding thick plates in the Reeve test. These factors would tend to accentuate any tendency of an electrode towards weld cracking at elevated temperatures, and it is known that the type of electrode used is prone to weld cracking under these conditions. A similar type of cracking has been observed by Rollason and Roberts.[2]

The results of the tests indicate that both steels have good weldability. They also have similar weldability, since equally severe conditions must be imposed on both steels to promote hard-zone cracking during welding.

MECHANICAL PROPERTIES OF THE NORMALISED AND TEMPERED PLATE

The mechanical properties of the two steels in the form of ½ in. and 1½ in. plate are given in Table III. The plates were normalised by soaking at 900 deg. C. followed by cooling in still air, and tempered (where specified in the table) at 600 deg. C.

EFFECT OF HEAT-TREATMENT TEMPERATURE ON THE MECHANICAL PROPERTIES

Mechanical tests were made on both steels after they had been heat treated in the form of ¾ in. plates. The heat treatment was carried out by soaking the plates at various temperatures for ½ hr. followed by cooling in still air. This treatment was undertaken in order to determine the effect of variations in the temperature of finishing of the rolling operation on the mechanical properties to be expected from rolled sections of the two steels.

Blanks for tensile tests and notched-bar impact tests were cut from each plate in the direction of rolling. The impact tests were made on a Hounsfield Balanced Impact machine, the energy of the blow being 48 ft.-lb. The averages of the three values obtained from each plate were converted to equivalent Izod values by multiplying by a factor of 2·4.

Heat treatment was carried out at 750, 850, 950, 1,050 and 1,150 deg. C., and the results of the mechanical tests made on the steels in these conditions are shown graphically in Fig. 1.

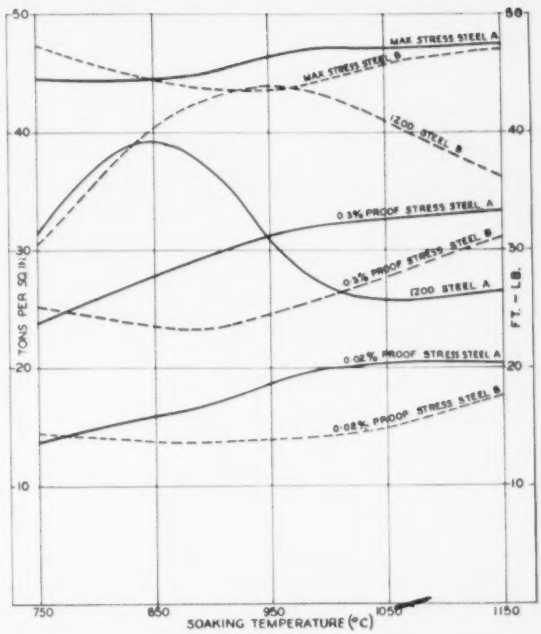


Fig. 1

The results show that with steel A, the best mechanical properties are obtained with soaking temperatures above 1,000 deg. C., when an 0·3 per cent. proof stress of 32–33 tons per sq. in. is obtained. This improvement in proof stress is accompanied, however, by a lowering of the notched-bar toughness. The proof stress of steel B decreases slightly with increase in soaking temperature up to 900 deg. C., but above this temperature there is a continual rise in proof stress with increase in soaking temperature; treatment at 1,150 deg. C. produces an 0·3 per cent. proof stress of 31 tons per sq. in. There is a corresponding decrease in notched bar toughness) but this is not so marked as with steel A.

A similar series of tests was made on 1½ in. plate, but on this thickness of plate the properties were not changed appreciably by variation in heat treatment temperature, and so these results are not included in the present report.

Table III.—Mechanical Properties of ½ in. and 1½ in. plate.

Plate Thickness (in.)	Steel	Condition	Yield Stress (tons/sq. in.)	0·5 per cent. Proof Stress (tons/sq. in.)	U.T.S. (tons/sq. in.)	R. of A. (per cent.)	Notched Bar Tests (ft.-lb.)
½	A	Normalised	—	31·0	45·3	56	—
	B	Normalised†	—	25·8	44·0	48	27 (Izod)
		Normalised and tempered†	28·5	—	37·7	61	95 (Izod)
1½	A	Normalised*	—	23·1	37·5	62	41 (Charpy)
		Normalised and tempered*	25·0	—	34·6	70	70 (Charpy)
	B	Normalised†	—	23·0	40·4	58	44 (Izod)
		Normalised and tempered†	27·9	—	37·4	68	90 (Izod)

† Average of results from United Steel Co. Ltd. and B.W.R.A.

* Average of results from Colvilles Ltd. and B.W.R.A.

The mechanical properties of steels A and B are lower than those of similar steels, i.e. Nos. 20 and 35 respectively of the experimental series.[1]

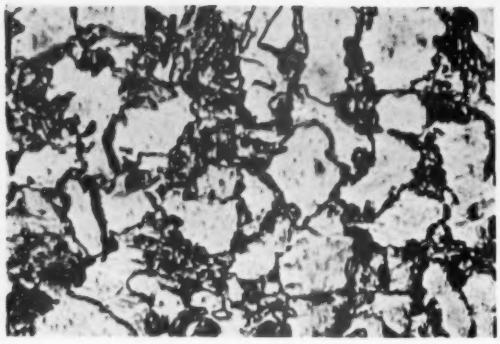


Fig. 2. Steel A. $\frac{3}{8}$ in. thick, heat treated at 750 deg. C.
0·3 per cent. proof stress: 23·9 tons per sq.in.

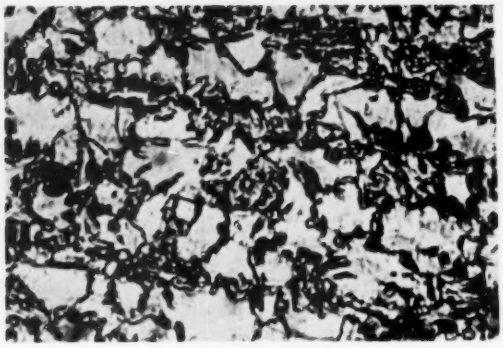


Fig. 5. Steel B. $\frac{3}{8}$ in. thick, heat treated at 750 deg. C.
0·3 per cent. proof stress: 25·25 tons per sq.in.

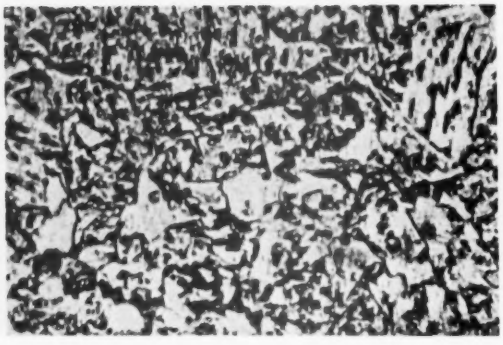


Fig. 3. Steel A. $\frac{3}{8}$ in. thick, heat treated at 950 deg. C.
0·3 per cent. proof stress: 31·3 tons per sq.in.

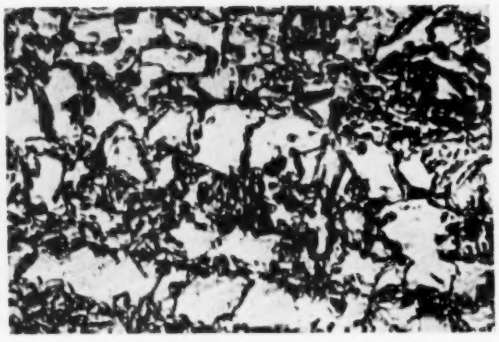


Fig. 6. Steel B. $\frac{3}{8}$ in. thick, heat treated at 950 deg. C.
0·3 per cent. proof stress: 24·5 tons per sq.in.

Fig. 4. Steel A. $\frac{3}{8}$ in. thick, heat treated at 1150 deg. C.
0·3 per cent. proof stress: 33·5 tons per sq.in.

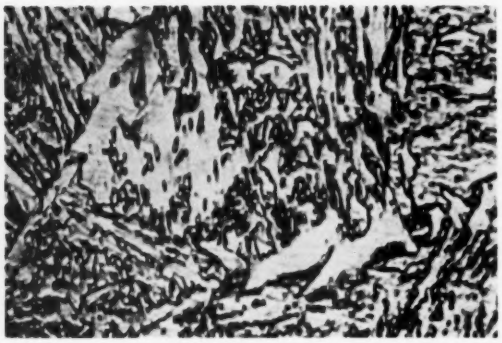


Fig. 7. Steel B. $\frac{3}{8}$ in. thick, heat treated at 1150 deg. C.
0·3 per cent. proof stress: 31·0 tons per sq.in.

Photomicrographs × 450 (*all specimens etched in 2 per cent. nital*)

RELATION BETWEEN MICROSTRUCTURE AND MECHANICAL PROPERTIES OF THE STEELS NORMALISED FROM VARIOUS TEMPERATURES

Sections for micro-examination were taken from the ends of three of the tensile test specimens cut from $\frac{3}{8}$ in. thick plate. These had been normalised from 750, 950 and 1,150 deg. C. respectively, and photomicrographs of the structures are shown in Figs. 2–7. The two steels when heat treated at 750 deg. C. have different structures, and the response of the two steels to heat treatment at the higher temperatures is also different. Steel A (Fig. 2), heat treated at 750 deg. C., has a structure with little indication of rolling direction. Steel B (Fig. 5), also heat treated at 750 deg. C., has a structure with the rolling direction clearly defined. The two steels heat treated at this temperature gave similar values of 0·3 per cent. proof stress and also similar notched-bar figures.

When the temperature of heat treatment is raised to 950 deg. C., steel A shows an appreciable change in structure, in particular a refinement of the grain, as shown in Fig. 3. These changes result in a marked rise in the 0·3 per cent. proof stress, but little alteration in notched-bar toughness. Steel B, however, shows little change in structure when treated at 950 deg. C., the direction of rolling remaining well defined (see Fig. 6). As a result the 0·3 per cent. proof stress is not changed, but the notched-bar toughness is increased.

With a further rise in heat treatment temperature to 1,150 deg. C., both steels show a similar coarse-grained structure, the grain being coarser in steel B than in steel A (see Figs. 4 and 7). These changes have resulted in a slight rise in the 0·3 per cent. proof stress for steel A with a drop in notched-bar toughness; the 0·3 per cent. proof stress for steel B has, however, risen sharply, and the notched-bar toughness has fallen appreciably.

CONCLUSIONS

The large casts of steel both show slightly better weldability, but lower mechanical properties, than the corresponding steels of the original experimental series.

It may therefore be possible to increase the alloy content of the steels slightly, with a view to obtaining improved mechanical properties, particularly in the thicker sections, while retaining good weldability.

ACKNOWLEDGMENTS

The authors would like to express their appreciation of the valuable discussions on the work given by members of the FM.8 Committee of the B.W.R.A. and the High Tensile Weldable Structural Steel Investigation Steering Committee of the Ministry of Supply, who jointly guided the investigation.

The authors are indebted to Messrs. Colvilles Ltd. and to the United Steel Co. Ltd., for making available mechanical test results on the steels.

REFERENCES

1. Ball, J. G., and Cottrell, C. L. M., The Weldability and Mechanical Properties of a Series of Low-Alloy Steels, *Journal of the Iron and Steel Institute*, **169**, (December, 1951), p. 321.
2. Rollason, E. C., and Roberts, R. R., Effect of Cooling Rate and Composition on the Embrittlement of Weld Metal, *Journal of the Iron and Steel Institute*, **166**, (October 1950), p. 105, and Correspondence relating to the paper; *Journal of the Iron and Steel Institute*, **168**, (July 1951), p. 259.

SELF-ADJUSTING ARC AND CONTROLLED-ARC WELDING PROCESSES

This review was prepared for the LM.7 Committee (on Self-Adjusting Arc and Controlled-Arc Welding Processes) of the British Welding Research Association.
The report is conveniently arranged in three parts. The first deals with the essential features of the processes, the second part is concerned with fundamental aspects of the processes, such as arc characteristics and material transfer and the third part deals with the information available on the welding of ferrous and non-ferrous materials.
The opinions expressed are not necessarily those of the authors or of the LM.7 Committee but every care has been taken to present an accurate assessment of the literature available, mainly from American sources, up to December, 1952.

By W. G. HULL,* A.I.M., and J. C. NEEDHAM,† B.Sc.

INTRODUCTION

Two new arc welding processes, both of which employ a consumable electrode and gaseous shielding of the arc, have been developed in recent years and have quickly become established in America as important methods of fabrication. Various terminology have been used to describe these processes but the authors prefer to use the terms Self-Adjusting Arc and the Controlled-Arc welding. The reasons for this choice of nomenclature have been discussed elsewhere[20]. With the self-adjusting arc process, welding can be carried out manually in all positions in plate thicknesses ranging from about $\frac{1}{8}$ in. to the maximum thickness available, while the controlled-arc process is used for mechanised welding of plate of $\frac{3}{8}$ in. thickness and over.

Since the first announcement was made of these new welding methods, a number of papers have appeared, mainly in the American technical press, giving details of the application of the processes to the welding of various non-ferrous and ferrous materials and data on arc characteristics. This review summarises the published information up to December 1952.

The first part of the review describes the essential features of both processes, the second part is mainly concerned with arc characteristics including material transfer and arc-length control, and the third part summarises available information on the welding of ferrous and non-ferrous materials. A short account of applications described in the literature is also included.

PART I.—ESSENTIALS OF THE PROCESSES.

SELF-ADJUSTING ARC

The operation of the self-adjusting arc process has been fully described in the literature[7, 9, 14]. A schematic diagram of the process is shown in Fig. 1 while Fig. 2 illustrates one design of commercial equipment. A thin, consumable bare-wire electrode is fed at constant speed through a manually operated welding gun, the arc being maintained between the end of the wire and the work-piece in an atmosphere of inert gas. Although there are certain differences in the designs of existing commercial equipment, they are essentially the same in their mode of operation. The wire is fed from a reel at a pre-determined and constant rate through a length of flexible hose to a guide tube in the barrel of the gun. Current is picked up by the wire as it travels through the guide tube which is directly connected to the cable from the power source. The handle of the gun has a trigger control which, when depressed, closes a welding contactor, opens a gas solenoid valve, and if the gun is water-cooled, starts the flow of water. There are two alternative methods for starting the motor which operates the drive rolls. In one method the drive motor starts feeding the wire when the trigger is depressed, while in the other the wire feeds forward only when the arc is established.

The process operates at current densities considerably higher than those used in other arc welding methods and this results in an arc having inherently self-adjusting characteristics, so that no external means of arc-length control is necessary. In addition, the material transfer ceases to be visibly globular and occurs in the form of a fine spray which is projected across the arc gap at high velocity. This spray or projected type of transfer enables welding to be carried out satisfactorily in all positions.

The range of electrode wire sizes used is from $\frac{1}{32}$ in. to $\frac{3}{32}$ in. diameter, the choice depending on the thickness of the plate to be welded and the welding conditions to be employed. At the present time, most equipment for the process uses direct current electrode positive, the power supplied by standard units of the generator or rectifier types.

* British Welding Research Association.
† Electrical Research Association.

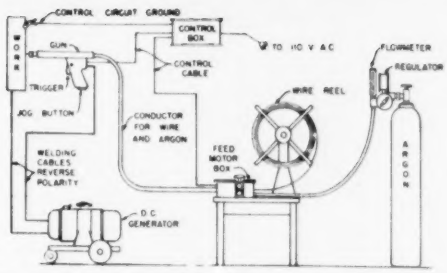


Fig. 1. Schematic diagram of self-adjusting arc process.

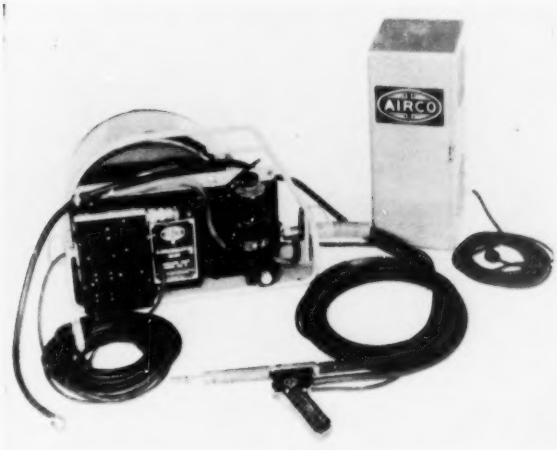


Fig. 2. Self-adjusting arc unit of American design.

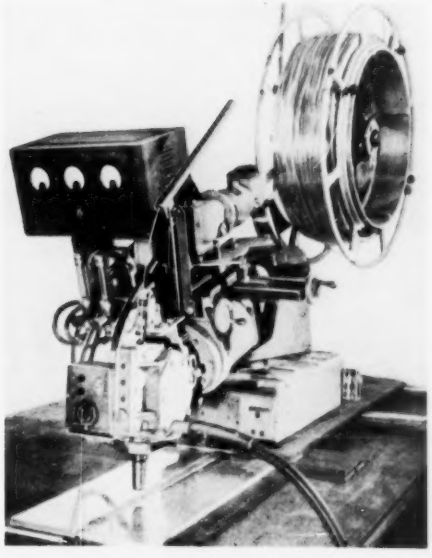


Fig. 3. Controlled arc head of American design.

CONTROLLED ARC

A typical controlled-arc head is shown in Fig. 3. The means of controlling arc length differ from the self-adjusting arc process in that changes in arc length are corrected by alterations in the rate at which the wire is fed. The operation of the apparatus is similar in principle to that employed in submerged-arc welding, the arc length being controlled from the arc voltage by electronic or other means. The equipment handles wire of heavier gauge than the manual process, the sizes being from $\frac{3}{32}$ in. to $\frac{3}{16}$ in. diameter. The process is mainly used in fields of application where fully-automatic welding is possible, the welding head being usually mounted on a carriage so that it may traverse the work-piece. This type of machine will weld at currents up to about 600 amps. and is normally used for downhand butt joints in material over $\frac{3}{8}$ in. in thickness. The process is not so suitable for fillet welding, the manual process being preferred for this type of joint.

PART II.—ARC CHARACTERISTICS

PROPERTIES

Arc Appearance

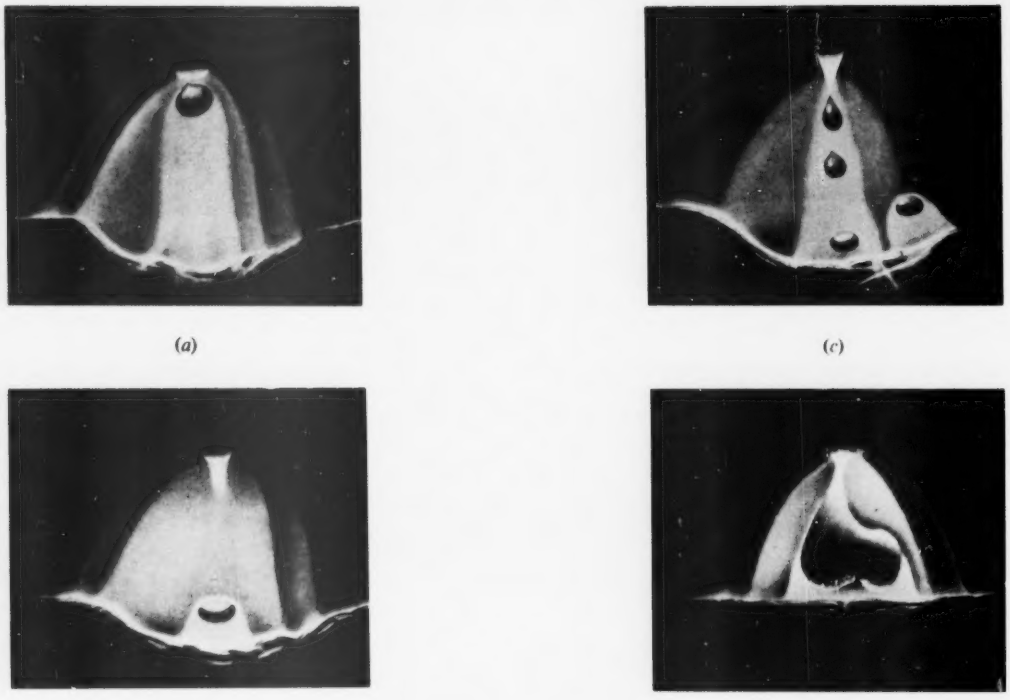
The general appearance and behaviour of these high current density arcs in an inert gas is much the same visually, (Fig. 5) as that resolved by high-speed cine-photography of up to 10,000 frames per sec. (Fig. 4a). The arc is roughly bell-shaped with the top just enveloping the electrode tip and exhibits three distinct zones[13]. The outer bell is faint and apparently not as hot as the inner one as it is often in contact with unmelted material. Practically all melting of the plate takes place within the inner bell which is always present and continuous from rod to plate and which is believed to be the main current carrying part. Cathode sputtering and an oxide cleaning action occurs at the negative end. The central zone is generally cylindrical and the most brilliant, but high-speed photography shows that it often disappears, especially with aluminium electrodes as shown in Fig. 4b. This zone consists, it is believed, of luminous metal vapour, which surrounds and often precedes the transferred droplets; and if a droplet strays in free flight the sheath goes with it (see Fig. 4c).

The emmission spectra of the arc consists of the characteristic lines of the shielding gas and metal vapour, with the continuous spectrum associated with an incandescent solid[15]. The dominant colours of the central zone in argon, are green for 5 per cent. Al-bronze, blue for 2 per cent. Mn-steel, orange red for aluminium and red with no central zone for the same material in helium.

Aluminium radiates mostly in the ultra-violet and its arc colour is mainly that of the shielding gas (note: this differs from the colour at low currents and pressures)[15]. The light intensity is high and even for photographic exposures of 1/100,000 sec. the addition of neutral density or colour filters are advantageous[13]. The absence of dense smoke gives a clearer view of the arc, but the radiation is greater when compared with normal metal-arc welding[22].

Material Transfer

For a given set-up there is a current below which the electrode forms large and erratic globules of several times its own diameter. As the current is raised this condition fairly suddenly changes to a rapid succession of just visible droplets of about the wire diameter[9, 13, 15, 17]. With further increase of current the transfer is too rapid to be seen and is often regarded as a spray (see Table I). High-speed photography shows that the material still transfers as droplets (see Fig. 4c) which are ejected from the rod at a sufficiently high velocity to permit all position welding.



(*a*) (*c*)

(*b*) (*d*)

Fig. 4. Illustrations based on high-speed photography of metal-arcs in argon.
(*a*) and (*b*) Aluminium electrode positive. (*c*) Steel electrode positive. (*d*) Aluminium electrode negative.

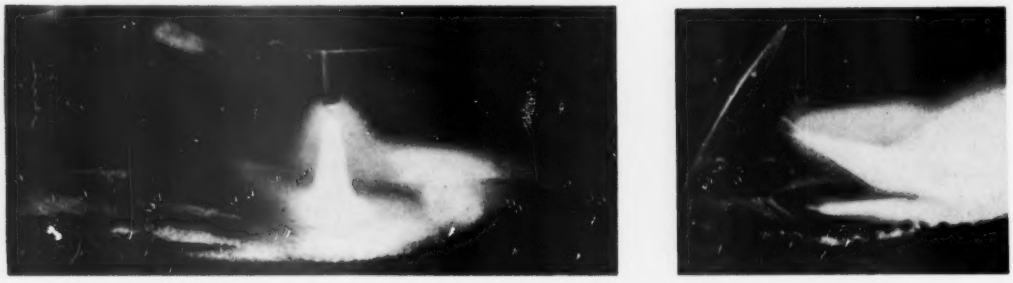
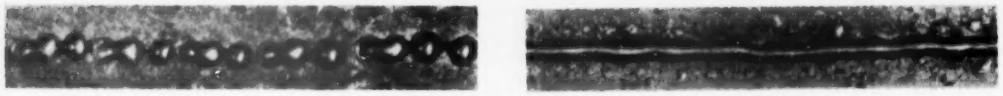


Fig. 5. Visual appearance of self-adjusting arcs in argon.
Left—Vertical electrode. *Right*—Electrode inclined at 30 deg. from the horizontal.



(*a*) (*b*)

Fig. 6. Stainless steel deposits with welding speed of 300 in. per minute.
(*a*) In argon. (*b*) In oxy-argon.

Table I.—Size and Frequency of Metal Transfer near the Threshold Current for $\frac{1}{16}$ in. diameter Aluminium Electrode Positive in Argon (Muller, Gibson and Roper[9]).

Arc Current (Amperes)	Average No. of Globules (per sec.)	Equivalent Length of Wire per Drop (in.)
120	3·6	$\frac{1}{8}$
140	34	0·07—just visible
160	49	0·05—not visible

Spatter is generally low in argon and slightly higher in helium giving a high overall deposition efficiency, e.g. 98 per cent. for carbon steel[22], and 99 per cent. for aluminium bronze[11]. The chemical composition of the deposited metal is practically the same as that of the wire[11, 15], as even highly reactive elements such as titanium are transferred without much loss. High vaporization losses however occur with zinc. Fig. 7 gives the average burn-off curves for a number of materials. The burn-off rate increases with current, but decreases with increase of arc length (arc voltage) at a given current, owing apparently to increased radiation losses[9].
For further data on material transfer see page 84.

Arc Voltage

The arc voltages for average working arc lengths are from 20–25 volts at 150 amps., to 30–35 volts at 500 amps. in argon with electrode positive[23]. Voltages in oxy-argon are similar [23] but are about 5–10 volts higher in helium[15].

The general voltage-current and length characteristics[15] when using argon, show, at constant arc length, a small rise of voltage with current of about 0·03 volts per amp., for aluminium (Fig. 8). Metal arcs normally have a substantially flat characteristic and this positive rise with current may be partly due to the resistance of the thin wire, especially at the tip[23]. The resistivities of common materials at room temperature are in microhm per cu. cm.: copper 1·7, aluminium 2·8, 2 per cent. Mn-steel 10, 8 per cent Al-bronze 35, stainless steel 70. Increasing the wire diameter reduces the arc voltage, e.g. 3 volts drop for $\frac{3}{32}$ in. dia. aluminium when compared with $\frac{1}{16}$ in. dia.[15].

The increase in arc voltage with length at constant current is roughly 15 volts/inch in argon and 25 volts/inch in helium[15]. Metal arcs commonly have voltage gradients of 50 volts/inch and at the lower gradients the wire feed control, where used as in controlled arc, needs to be more sensitive to maintain a given arc length[14]. The voltage gradient tends to increase at short arc lengths[15] as has been found for other metal arcs[2]. Note in Fig. 8 the curves are averages of many readings as there was appreciable scatter and the arc length taken is the projected visible length, i.e. rod to plate gap, and does not include the crater if any. Under given conditions a long arc (higher arc voltage) gives a quiet arc, shallow penetration and wide bead[22].

Arc Stability

The arc at these high current densities exhibits a mechanical stiffness, i.e. the arc tends to remain in line with the rod irrespective of its inclination to the plate[9, 15] (see Fig. 5). This is due to a force field arising from the arc current flowing in the field set up by the current in the rod, as shown in Fig. 9. The force increases as the square of the current and is greater for a smaller diameter wire, especially near the rod tip[15].

The arc is also electrically stable and apparently not disturbed by the projected material transfer. The small droplets of metal do not bridge the gap except at very short arc lengths, and the absence of short circuits avoids the difficulty of re-igniting the arc when using a generator of slow response[15]. The arc is initiated by touch starting, and as direct current is used, the problem of cyclic arc re-ignition does not arise. Also at high current densities with the correspondingly high rates of wire feed, the arc length is self-adjusting, i.e. no arc length control based, say, on arc voltage is required. The wire feed rate can be fixed and a change of arc length is then corrected by a change in the arc burn-off rate until the original length is restored, i.e. the burn-off rate decreases with increase of arc length and vice-versa[9, 15]. *For further data see section on arc length control.*

Effect of Shielding Atmospheres

The shielding gas is usually 99·8 per cent. argon at 20–50 cu. ft./hr. flow rate. Helium is also used and gives a greater arc voltage and penetration at the same current and arc length, but requires a higher flow rate than argon[14, 24]. Argon gives less spatter and a more pronounced oxide cleaning on aluminium[14]. Mixtures of argon in helium have been used to reduce spatter[12].

Addition of between 1 per cent. and 5 per cent. flow of oxygen to argon reduces the size of the transferred droplets and increases their frequency without much change in burn-off rate. Oxy-argon (or sigma argon) has been found suitable for carbon steels, stainless steels and under limited conditions,

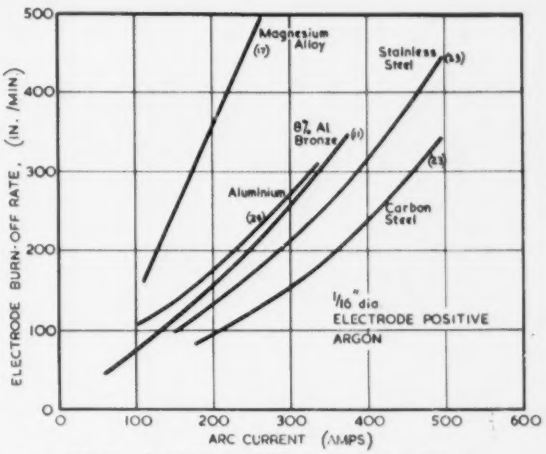


Fig. 7. Average burn-off rate/arc current curves.

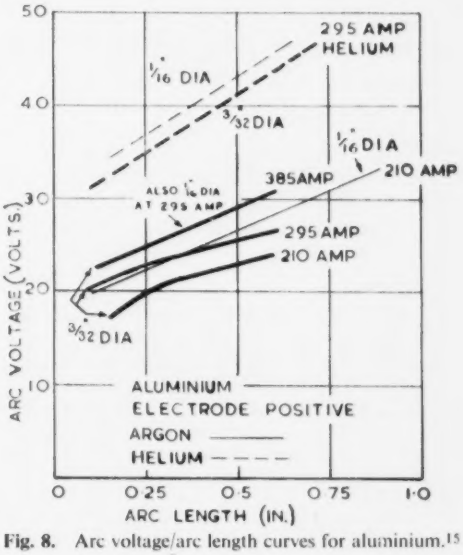


Fig. 8. Arc voltage/arc length curves for aluminium.[15]

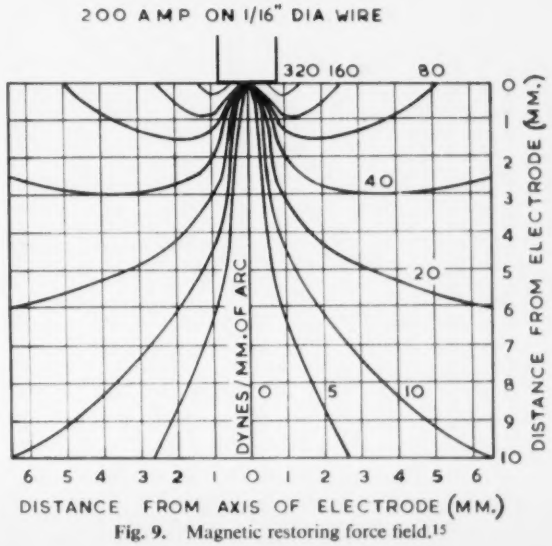


Fig. 9. Magnetic restoring force field.[15]

for aluminium. Higher welding speeds are possible without undercutting or lack of coalescence and lower current densities can be used[24]. Oxy-argon reduces the minimum current required for spray-type material transfer.* This reduction is advantageous for carbon steels and stainless steels for which the threshold currents are about double that for aluminium[24]. However, adding oxygen to helium, raises the threshold current for steel[23].

Effect of Power Supply

Standard d.c. generators, including constant potential multi-operator units and rectifier types, are suitable and variations in open circuit voltage from 70 volts to the maximum usually available seem to have no significant effect on arc characteristics. Alternating current can also be used but more specialised types of transformer are required[14].

The arc is generally run with the wire electrode positive (reverse polarity), though the burn-off rates for aluminium, carbon steel and stainless steel are higher for electrode negative[22, 24]. This latter polarity has been used in particular cases such as stainless steel and aluminium alloys in oxy-argon[16].

MATERIAL TRANSFER AND ELECTRODE BURN-OFF

Mechanism of Transfer

The principal forces or effects believed to be responsible for the transfer of metal from rod to plate include gravity, magnetic pinch effect, surface tension and expansion of gases[3]. During a short-circuit, the surface tension and pinch effect with or without the aid of gravity govern the material movement. In the absence of shorting, the transfer is believed to be due to the explosive expansion of gases at the rod tip and/or the rapid vaporization of the final neck attaching the globule to the rod, since overhead welding with a pure gas-free iron rod is not possible at normal current densities.

Early work[1] on bare steel electrodes in inert gases showed that the rod formed large globules which transferred under gravity every few seconds in spite of gas inclusions. There was no crater and little penetration. Adding oxygen to the argon atmosphere caused the metal to transfer as a stream of smaller globules with the formation of a crater and improved penetration, and some increase in burn-off rate. Adding a little antimony to the rod also reduced the globule size by lowering the surface tension and aided crater formation. These tests showed that penetration could be obtained without a crater and that oxygen was necessary to crater formation—possibly by affecting the surface tension.

The pinch effect, which increases as the square of the current density, is predominant at the densities used in the self-adjusting arc process. The transfer of material as small molten globules from the rod tip at a high velocity is believed to be due to the pinch effect. The burn-off rate increases approximately proportionally with the current, but below the threshold current for projected material transfer (see Table II) the rod forms large and erratic globules at the rate of a few per second. At the threshold current, the transfer changes fairly suddenly to a stream of small and almost uniform droplets which can just be seen leaving the rod tip (Table I). Further increase of current reduces the droplet size[15] (see Fig. 10) and increases their frequency, this so-called spray transfer being too rapid to resolve by eye.

High-speed photography up to 10,000 frames/sec. shows that at high currents more than one globule is in flight at a time, especially for steel[13] (Fig. 4c). The transferring globule rapidly accelerates to a high velocity on leaving the rod tip and traverses the arc at a substantially constant speed[13], and can travel a considerable distance against gravity[15]. Table 3 gives typical data derived from high-speed photography. Note that the feed rate, deduced from the globule size and frequency, is excessively high so presumably the globules are expanded or hollow.

With electrode negative for aluminium in argon, the rod forms only large globules (see Fig. 4d) at currents which give projected transfer with electrode positive. The large globules appear to be repulsed by the arc with cathode sputtering on the underside and the globules finally transfer by gravity alone[13]. Much greater currents lead to a rapid metal transfer, but this is still different from that with electrode positive. The burn-off rate with electrode negative is up to twice that for the other polarity[22, 23].

The high current density results in penetration even at comparatively low currents when the crater itself is small or absent. Deep craters form at heavy currents, e.g. $\frac{5}{16}$ in. crater for aluminium electrode positive in argon at 600 amp.[9] At the same current and length, the penetration is higher in

* For a given material, electrode size and shielding gas, the minimum current at which spray-type transfer is first observed may be called the threshold current.

Table II.—Threshold Currents for Transition to Projected Material Transfer of Small Globules.

Material (Electrode Positive)	Rod Diameter (in.)	Threshold Currents (Amperes)	
		Argon	Helium
Aluminium[15]	$\frac{1}{16}$	130–150	—
8 per cent. Al-Bronze[15]	$\frac{1}{16}$	175–200	—
Magnesium Alloy[17] ...	$\frac{1}{16}$	200–220	240–260
Magnesium Alloy[17] ...	$\frac{3}{32}$	280–300	350–370
2 per cent. Mn-Steel[15]	$\frac{1}{16}$	220–240	—

Table III.—Data on Material Transfer Derived from High-Speed Cine-Photography (Gillette and Breymeier[13]).

	Electrode $\frac{1}{8}$ in. diameter in Argon		
	Aluminium	Steel	Steel
Arc current, rod positive (amp.)	400	500	600
Arc length (in.)	0·65	0·78	0·64
Rod Speed (in./min.) ...	100	80	100
Drop radius (in.)	0·035	0·035	0·027
Drop volumes (cu. in. $\times 10^{-5}$)	18	18	8
Particles per second ...	293	543	707
Particle velocity (in./sec.)...	380	484	904
Acceleration (in./sec.$^2 \times 10^{-5}$)	1	3	6
NOTE: Approx. rod speed in inches/minute from drop volume and particles second ...	260	480	280

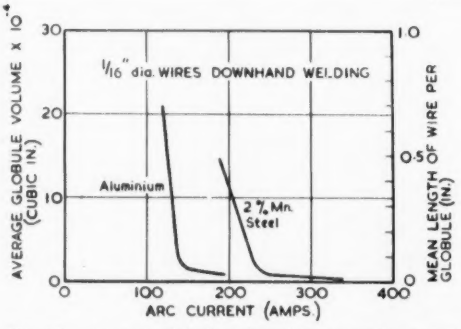


Fig. 10. Average globule volume/arc current curves.[15]

helium than in argon, but the latter gives less spatter. For a given arc, the penetration decreases with increase in arc lengths[22]. Spatter is usually negligible except near the threshold current for globule transition when the material tends to bounce out of the weld pool[17]. Short circuits, especially with large globules, also tend to produce spatter. All elements except zinc, and to a lesser extent titanium, in the rod material, are transferred substantially without loss. The fine, black powder alongside the weld bead is finely divided electrode material, probably arising as vapour from the incandescent rod tip[15].

For large diameter electrodes (or at comparatively low currents) the current density may be too low for projected material transfer, but welding can still be performed downhand. Wire feed-rate control is used under these conditions as the self-adjustment at low burn-off rates may not be adequate. Large diameter electrodes are more economical and their surface impurities relatively less. For a given current, more metal is deposited for a larger rod when welding aluminium, but less in the case of carbon steel in oxy-argon[14, 22, 24] (see Fig. 11).

Adding a few per cent. oxygen to the argon (" sigma " argon) increases the rate of transfer, but decreases the globule size without much change in the burn-off rate. The threshold current for projected material transfer is lowered for ferrous materials, and the welding speed can be increased without undercutting or lack of coalescence. By welding on to a rapidly moving plate or strip, the transferred metal can be resolved into individual drops and in addition, the tracking can provide data on arc root movement[6]. Fig. 6 compares the appearance of the deposited metal at 300 inch/minute traverse rate for stainless steel in argon and oxy-argon.

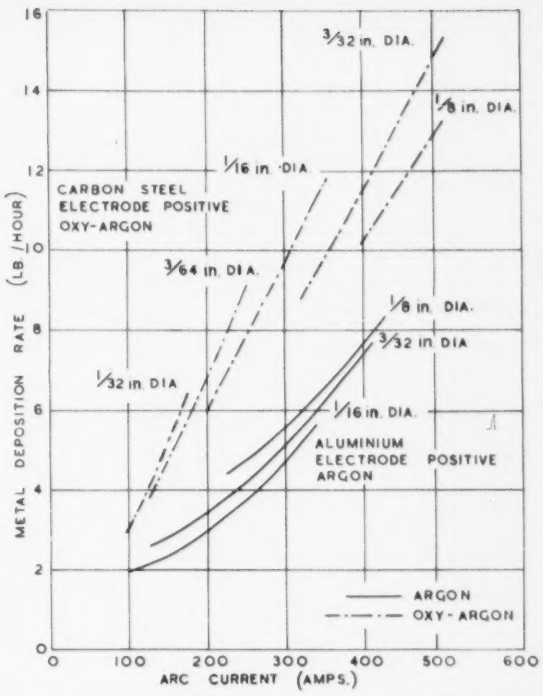


Fig. 11. Deposition rate/current curves for various wire diameters for carbon steel and aluminium.[24]

Burn-Off Rate

The burn-off rate is constant for a given welding arc, but it varies with the arc length, current and atmosphere, and the electrode material, diameter and polarity. The burn-off rate for a given rod decreases with increase of arc length (arc voltage) at constant current[9, 15], i.e. in spite of increased arc power there is less consumption of the rod at greater arc lengths (see Fig. 12 for aluminium and an aluminium-bronze). This property contributes directly to the self-adjustment of the arc length. A possible explanation of the decrease in burn-off rate is that the extra arc power is confined to maintaining the arc column over a greater length[15], and that the rod tip absorbs much less radiant energy from the plate[9]. The burn-off rate is also affected by the length of wire from the current contact to the arc, but this is only noticeable for materials of high resistivity, such as stainless steel[15]. Burn-off increases at approximately the same rate as current at a given arc length (see Fig. 13 for carbon steel in oxy-argon for both polarities).

The average arc voltage in practice tends to be lower at low currents than at high currents, thus giving a relatively higher burn-off or greater efficiency at the lower currents. The minimum current that can be used is limited by the material transfer which tends to become too globular and erratic giving comparatively high spatter loss. The maximum usable current is not well defined, but it is limited by the increased penetration, and for carbon steels by the incidence of porosity at very high current densities[22]. In the case of aluminium, the upper limit is imposed by the occurrence of oxide folds[23].

Fig. 14 gives the published curves of average burn-off rates against current for average working arc lengths for aluminium wires with various arc atmospheres and electrode polarities[9, 14, 23, 24]. Similar data are plotted in Fig. 15 for carbon steel[22, 23, 24] and in Fig. 16 for stainless steel[23].

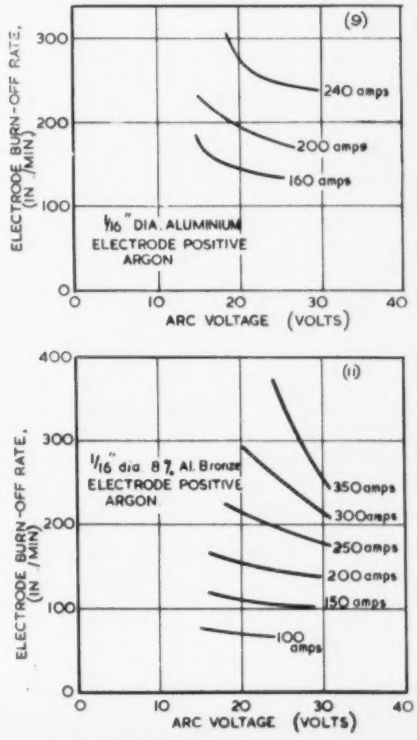


Fig. 12. Burn-off rate/arc voltage curves at constant currents.[9,11]

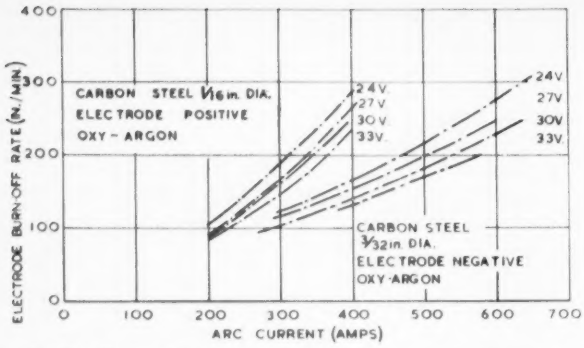


Fig. 13. Burn-off rate/current curves at constant arc voltages for carbon steel.[22]

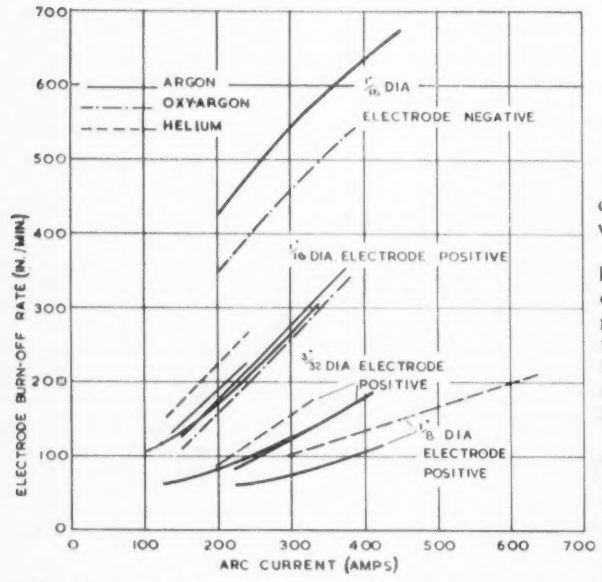


Fig. 14. Burn-off rate/arc current curves for aluminium.[9 14 23 24]

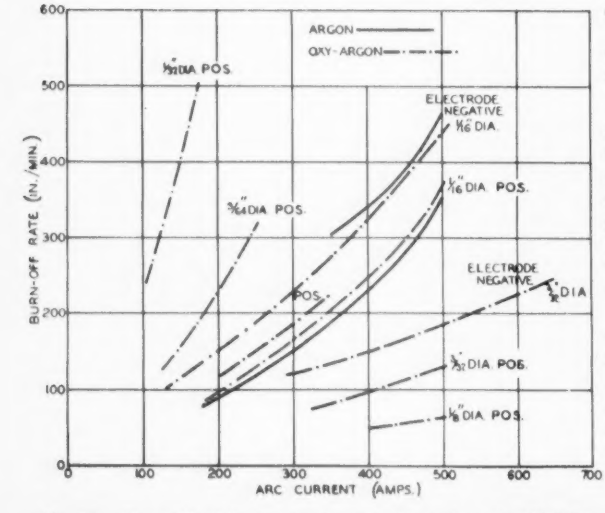


Fig. 15. Burn-off rate/arc current curves for carbon steel.[22 23 24]

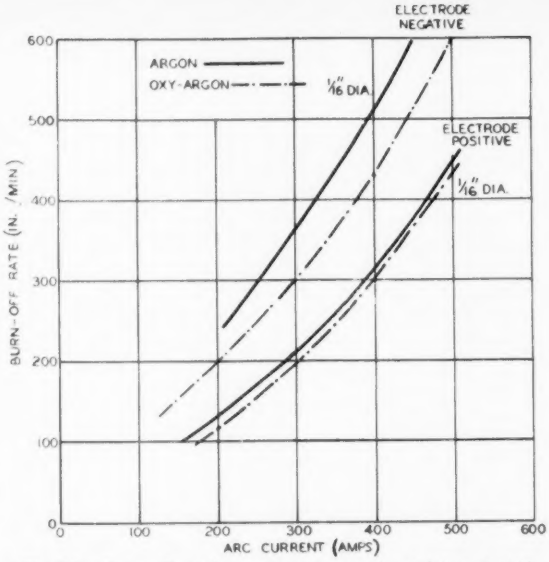


Fig. 16. Burn-off rate/arc current curves for stainless steel.[23]

Fig. 7 gives the burn-off rates for various materials against current for average working arc lengths for $\frac{1}{16}$ in. diameter wires, electrode positive, in argon[11, 17, 22, 23].

The burn-off rate for a given arc current is higher in helium than in argon for aluminium[9], but lower in the case of a magnesium alloy[17]. Although adding oxygen to argon greatly changes the size and frequency of the material transfer, the burn-off rate is substantially unchanged. The burn-off rate is a little lower for aluminium and stainless steel and with electrode negative for carbon steel, but a little greater for carbon steel, electrode positive[23].

The burn-off rate is higher at a given current with the electrode negative than with the electrode positive. The increase in burn-off rate varies between 25 per cent. and 50 per cent. for carbon steel, 50 per cent-75 per cent. for stainless steel, and 50 per cent.-100 per cent. for aluminium[23]. With electrode negative (straight polarity) the penetration is less and higher currents are required to obtain rapid transfer of small globules.

Table IV summarizes the approximate burn-off rates per ampere for various materials, wire sizes, atmosphere and electrode polarity.

ARC LENGTH CONTROL

Self-Adjusting Arc

Arc length control depends on the balance between melt rate and wire feed rate, i.e. to change the arc length, the feed rate must temporarily be greater or less than the melt rate and then return to the new equilibrium. The arc current, at the given arc length and arc voltage, determines the melt rate for a particular welding set up. The wire feed rate is pre-set in the self-adjusting arc, but in other processes the feed rate is controlled according to the arc voltage (arc length).

At the high current densities, the arc burn-off rate decreases with increase of arc voltage (arc length) at constant current[9, 11, 22], (see Fig. 12). This property is believed mainly to account for the self-adjusting effect. Increase of arc length also reduces the terminal part of the wire from the torch and for materials of high specific resistance, e.g. stainless steel, there is a further decrease in melt rate due to the decreased resistance heating[15].

The arc voltage also determines the current in the welding circuit according to the voltage—current characteristic of

Table IV.—Burn-off Rate per Ampere—inches/minute/ampere.

Wire Material	Wire Diameter (in.)	Electrode Positive			Electrode Negative	
		Argon	Oxy-argon	Helium	Argon	Oxy-argon
Aluminium[9, 14, 23, 24]	1/16	0·9	0·88	1·1	1·8	1·5
	5/32	0·43	—	0·53	—	—
	1/8	0·27	—	0·34	—	—
Carbon Steel[22, 20, 24]	5/32	—	2·7	—	—	—
	3/4	—	1·2	—	—	—
	1/16	0·58	0·63	—	0·88	0·83
	5/32	—	0·25	—	—	0·39
	1/8	—	0·12	—	—	—
Stainless Steel[23]	1/16	0·78	0·74	—	1·2	1·1
8 per cent. Al-Bronze[11]	1/16	0·81	—	—	—	—
Magnesium Alloy[17]	1/16	1·7	—	1·5	—	—

NOTE: In all cases the second decimal place is not necessarily significant.

the power source. Since this characteristic is drooping, the increase of arc voltage with length decreases the current and hence the arc burn-off rate. This property also gives rise to the self-adjusting effect[5, 7, 9, 14]. Thus, if the arc length is momentarily increased, the melt rate is reduced and, as the wire feed rate is constant, the arc length shortens until equilibrium is regained and vice-versa. Also, if the current is increased by change of machine settings, the arc length increases until the burn-off rate is brought to the equilibrium value. Conversely, if the wire feed rate is increased the arc length shortens until the melt rate reaches the required value[7].

The amount of self-adjustment depends on the length variation that can be accepted, but at high burn-off rates, of the order of 200 inches/min., the arc is maintained within reasonable limits once the wire feed rate is correctly set for the given welding current and materials. The self-adjustment is not unlimited as the arc can be broken by rapidly withdrawing the torch, also the feed speed needs to be closely held[14], and the generator output characteristics should not vary[22].

Controlled Arc

Where the degree of self-adjustment is inadequate, i.e. it takes too long for good welding for a length variation to be corrected owing to the small change in burn-off rate, the wire feed rate must also be altered. In manual metal-arc welding where burn-off rates are of the order of 25 inches/min., the operator controls the feed rate according to a visual estimate of arc length. For higher melt rates or for continuous wire, the operator is replaced by a machine, as in automatic welding or controlled arc, which alters the feed rate according to arc voltage (and indirectly according to arc length). The overall compensation is then due to the sum of the inherent change in burn-off rate if any, and the controlled change in wire feed rate[4].

Sensitivity

In the theoretical comparison[4] of the response of self-adjusting and controlled arcs, the difference (δ R) between the melt and wire feed rate is taken as proportional to the disturbance or change of arc length δ L, viz: $\delta R = C\delta L$. Also $\delta R = C\delta V/E$ where E is the voltage gradient and δ V the voltage change corresponding to δ L.

A disturbance δ L in length is thus corrected to δl (or a voltage δ V to δ v) in a time t given by:

$$t = \frac{1}{C} \text{Log}_e \frac{(\delta L)}{(\delta l)}, \text{ or } \frac{1}{C} \log_e \frac{(\delta V)}{(\delta v)}$$

The control sensitivity is defined as the excess feed rate per volt change in the arc, i.e. $\delta R/\delta V$.

In controlled arc, the design of the automatic head gives directly the change of wire feed rate per volt applied to the mechanism, i.e. the sensitivity[4]. Since $\delta R/\delta V = C/E$ this also gives the value of C knowing the arc voltage gradient which is generally about 20–50 volt/inch. For the self-adjusting arc the wire feed rate is constant, but the sensitivity at a mean arc length is given by the change in arc burn-off rate with current $\delta R/\delta I$ multiplied by the change in arc current with arc voltage $\delta I/\delta V$ due to the power source characteristics[4, 5]. As the burn-off and voltage-current characteristics are not linear over wide ranges, the sensitivity and constant C so calculated apply to relatively small deviations from the working point.

The sensitivity values serve as a criterion to compare the practical performance of different control systems, but within the limits required for satisfactory welding, the absolute value is not important. The sensitivity of the self-adjusting arc can be changed by altering the power source characteristic or by working at a different arc length[4, 15]. Where the arc voltage gradient is low, the sensitivity of conventional automatic heads can be raised to compensate[14] for this effect.

The change of arc length with time caused by making weld runs over a stepped plate or other profile, indicate for a practical set-up the overall self-adjustment or the response of controlled arc[15].

Similarly, the relative amplitude of motion of the wire tip when the plate is oscillated vertically at various sinusoidal frequencies gives the time constant of the control system and determines the degree of compensation. Assuming that the rate of correction is proportional to the length displacement from equilibrium, the relative amplitude response R is given by $R = (1 + 4\pi^2 f^2 T^2)^{-\frac{1}{2}}$ where T is the time constant and f the frequency of oscillation[15]. Fig. 17 gives

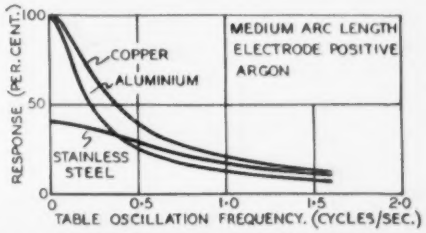


Fig. 17. Frequency response curves for aluminium, copper and stainless steel.[15]

typical frequency response curves for the self-adjusting arc for different materials at average arc lengths and Fig. 18 shows the effect of arc length on the frequency response curve for aluminium. Changing the arc length from $\frac{1}{8}$ in. to $\frac{1}{4}$ in. is also roughly equivalent for $\frac{1}{16}$ in. diameter aluminium to changing the generator open circuit voltage from 50 to 95 volts. The maximum response of 40 per cent. for stainless steel is attributed to the resistance heating effect of the wire projecting from the current contact.

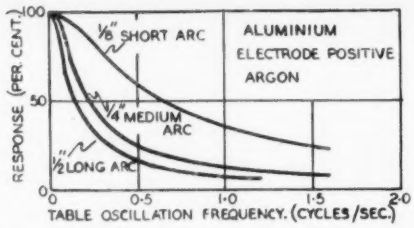


Fig. 18. Effect of arc length on frequency response for aluminium.[15]

PART III.—WELDING DATA.

WELDING OF ALUMINIUM ALLOYS

General Information

Work on the welding of aluminium alloys has been reported[7, 9, 10, 14]. The parent materials most commonly welded by these processes are the work-hardening alloys 2 S, 3 S, 4 S, 52 S and the heat treatable alloy 61 S. Two types of electrode wire have been used, namely, 2 S and 43S. The nominal compositions of these materials are given in Table V together with the nearest British equivalent specification. Welding is normally carried out with electrode positive.

Welds made by these processes are often found to contain porosity for which hydrogen is thought to be mainly responsible. Vacuum fusion analyses of samples of porous welds have shown this gas to be present in sufficient volume to account for the porosity. During welding, atomic hydrogen formed by dissociation of hydrogen-containing compounds in the arc is readily soluble in the liquid metal, but is rejected from solution on solidification. At this stage, gas bubbles are formed which tend to escape from the solidifying weld pool, but with high cooling rates, some of the gas is entrapped in the weld metal forming spherical gas pockets. Possible sources of hydrogen include hydrocarbons, moisture and hydrated oxide films on both the surfaces of the wire and plate. Improved results were obtained by degreasing the wire and porosity was further reduced when the oxide film on the wire was completely removed. Cleaning the wire was more effective than treating the prepared edges of the plate, since with the former the surface area involved is much greater. Porosity can be controlled to some extent by a welding technique involving a reciprocating motion of the arc to promote agitation of the weld pool thus assisting the escape of gas before the weld metal solidifies. It is also reported that more porosity is encountered when a short arc length, e.g. $\frac{1}{8}$ in. is employed and arc lengths of $\frac{3}{16}$ in. to $\frac{1}{4}$ in. are preferred. Porosity in vertical and overhead welds is more difficult to eliminate as in these positions a high rate of solidification is essential to prevent the weld metal from running out of the joint. With both the self-adjusting and controlled arc processes, sound welds can be made in the downhand position which are acceptable under pressure vessel standards. If no particular precautions are taken to eliminate porosity, welds can still be obtained with good mechanical properties and which are suitable for many applications[9].

Some workers[9] prefer helium for shielding purposes as smoother beads of better shape are produced with deeper penetration than with argon. There is also less tendency for porosity when using helium; however more spatter is experienced and this may be overcome by diluting helium with 10 to 30 per cent. argon. Herbst[14], on the other hand, prefers argon to helium on the grounds of less spatter, a more effective cleaning action and less gas consumption. Breymeier[23] reports that it is possible under certain conditions to weld with electrode negative in either a helium or oxy-argon atmosphere.

Controlled Arc

Welding with this type of equipment is usually carried out in the range of 300–650 amps. The process is suitable for downhand butt welds in plates of $\frac{3}{8}$ in. thickness and over[9], although it has been used successfully for thin sheet at high welding speeds[16]. Wire from $\frac{3}{32}$ in. to $\frac{3}{16}$ in. diameter can be used but $\frac{1}{8}$ in. diameter wire is the preferred size. Porosity is less of a problem in deposits made by this process as relatively large weld pools are involved and the gas has more chance to escape[9]. Typical welding conditions and edge preparations for butt joints in 61 S-T plate of different thicknesses are given in Table VI, while mechanical properties obtained from butt welds are listed in Table VII.

Self-Adjusting Arc

The process is applicable to all types of butt and fillet joints in plate thicknesses of $\frac{3}{16}$ in. and over. Welding speeds may be as high as 50 in. per minute but are usually limited to 20-25 in. per minute. Welding data for butt and fillet welds in various thicknesses of plate are given in Tables VIIIa and VIIIb. Burn-off rate curves for various sizes of aluminium wire are included in Figs. 7 and 14 while the effect of arc voltage on arc length is shown in Fig. 8.

Details of mechanical properties exhibited by butt welds in various alloys made by the process are given in Tables IXa and IXb. Shear tests obtained from specimens machined from long double-tee tests in $\frac{1}{4}$ in. 61 S plate welded with

Table V.—Nominal Composition of Aluminium Alloy Plate and Wire.

American Specification	Similar British Specification	Al (per cent.)	Si (per cent.)	Cu (per cent.)	Mn (per cent.)	Cr (per cent.)	Mg (per cent.)	Zn (per cent.)
2 S	B.S. 1477 PIC	99 min.	—	—	—	—	—	—
3 S	B.S. 1470 NS3	Bal.	—	—	1·2	—	—	—
4 S	—	Bal.	—	—	1·2	—	1·0	—
14 S	B.S. 1477 HP15	Bal.	0·8	4·4	0·8	—	0·4	—
43 S	B.S. 1474 NW21	Bal.	5·0	—	—	—	—	—
52 S	B.S. 1477 NP4	Bal.	—	—	—	0·25	2·5	—
61 S	B.S. 1477 HP10	Bal.	0·6	0·25	—	0·25	1·0	—
75 S	D.T.D. 683	Bal.	—	1·6	0·2	0·30	2·5	5·6

Table VI.—Typical Welding Conditions for Butt Welds in 61 S-T Plate made by the Controlled-Arc Process (Herbst[14]).

Thickness (in.)	Passes	Current D.C.R.P. (amp.)	Welding Speed (in./min.)	Wire Diameter (in.)	Argon Flow (cu. ft./hr.)	Edge Preparation
$\frac{1}{4}$	1	330	48	$\frac{5}{32}$	35	Square.
$\frac{1}{2}$	1	345	12	$\frac{1}{8}$	50	70 deg. included angle, $\frac{3}{16}$ in. deep.
$\frac{1}{2}$	2	375	12	$\frac{1}{8}$	50	Back chip, 70 deg. included angle, $\frac{3}{16}$ in. deep.
$\frac{3}{4}$	1	470	12	$\frac{1}{8}$	60	70 deg. included angle, $\frac{3}{16}$ in. deep.
$\frac{3}{4}$	2	470	12	$\frac{1}{8}$	60	Back chip, 70 deg. included angle, $\frac{3}{16}$ in. deep.
$1\frac{1}{2}$	1	420	5	$\frac{1}{8}$	60	" U " groove, $\frac{1}{4}$ in. deep.
$1\frac{1}{2}$	2	435	4	$\frac{1}{8}$	60	Second pass on first side.
$1\frac{1}{2}$	3	435	4	$\frac{1}{8}$	60	Back chip " U " groove, $\frac{1}{4}$ in. deep.

Table VII.—Mechanical Properties of Butt Welds in Aluminium Alloy Plate made by the Controlled-Arc Process (Muller, Gibson and Roper[9]).

Plate Thick. & Comp. (in.)	Wire	Type of Test	U.T.S. (ton/ sq. in.)	Angle of Bend	Location of Fracture
$\frac{3}{4}$ in. 2 S	2 S	Transverse tensile	5·8	—	Plate
$\frac{3}{4}$ in. 2 S	2 S	Guided side bend	—	180 deg.	—
1 in. 3 S	2 S	All weld metal tensile	8·0	—	—
1 in. 3 S	43 S	All weld metal tensile	10·0	—	—
1 in. 3 S	2 S	Transverse tensile	7·1	—	Plate
1 in. 3 S	2 S	Free bend	—	130 deg. and 180 deg.	—
1 in. 3 S	2 S	Guided side bend	—	180 deg.	—
$1\frac{1}{2}$ in. 3 S	2 S	Transverse tensile	8·4	—	Weld
$1\frac{1}{2}$ in. 3 S	2 S	Transverse tensile at —195 deg. C.	12·4	—	Weld
$1\frac{1}{2}$ in. 3 S	2 S	Guided side bend at —195 deg. C.	—	180 deg.	—
$\frac{3}{4}$ in. 61 S	43 S	Transverse tensile	12·3	—	Plate
$\frac{3}{4}$ in. 61 S	43 S	Transverse tensile after heat treatment	20·0	—	Weld

Table VIIIa.—Welding Procedures for Butt Welds, made by the Self-Adjusting Arc Process in Aluminium Plate (Waite[21]).

(i) *Overhead Butt Welds with Downhand Back Runs.*

Preparation: 60 deg. Vee with $\frac{t}{3}$ root face; $\frac{1}{16}$ in. maximum gap; temporary aluminium backing on top side; root back-chipped.

Plate Thickness (in.)	Run	Electrode Size (in.)	Current (amp.)	Wire Feed (in./min.)	Welding Speed (in./min.)
$\frac{1}{4}$	1	$\frac{1}{16}$	225	192	12
	back	$\frac{1}{16}$	225	192	12
$\frac{3}{8}$	1	$\frac{1}{16}$	275	235	14
	2	$\frac{1}{16}$	275	235	14
	back	$\frac{1}{16}$	200	176	13
$\frac{1}{2}$	1	$\frac{1}{16}$	275	235	16
	2	$\frac{1}{16}$	275	235	16
	3	$\frac{1}{16}$	275	235	16
	back	$\frac{1}{16}$	275	235	16

(ii) *Horizontal Butt Welds.*

Preparation: 50 deg. single Vee (40 deg. on lower and 10 deg. on upper plate); no root face; $\frac{1}{8}$ in. to $\frac{1}{16}$ in. gap; temporary aluminium backing.

Plate Thickness (in.)	Run	Electrode Size (in.)	Current (amp.)	Wire Feed (in./min.)	Welding Speed (in./min.)
$\frac{1}{4}$	1	$\frac{1}{16}$	225	192	12
	2	$\frac{1}{16}$	225	192	12
	back	$\frac{1}{16}$	225	192	12
$\frac{3}{8}$	1	$\frac{1}{16}$	290	242	12
	2	$\frac{1}{16}$	225	192	10
	back	$\frac{1}{16}$	225	192	10
$\frac{1}{2}$	1	$\frac{1}{16}$	300	254	10
	2	$\frac{1}{16}$	300	254	10
	3	$\frac{1}{16}$	225	192	8
	back	$\frac{1}{16}$	225	192	8

(*Table VIIIa contd. over page*)

Table VIIIa—*continued*
(iii) *Vertical Butt Welds.*
Preparation: 60 deg. Vee with $\frac{1}{32}$ in. maximum root face; $\frac{1}{16}$ in. maximum gap; temporary aluminium backing; root back-chipped.

Plate Thickness (in.)	Run	Electrode Size (in.)	Current (amp.)	Wire Feed (in./min.)	Welding Speed (in./min.)
$\frac{1}{4}$	1	$\frac{1}{16}$	170	195	12
	2	$\frac{1}{16}$	170	195	12
	back	$\frac{1}{16}$	170	195	12
$\frac{3}{8}$	1	$\frac{1}{16}$	275	235	12
	2	$\frac{1}{16}$	225	192	10
	back	$\frac{1}{16}$	225	192	10
$\frac{1}{2}$	1	$\frac{1}{16}$	275	235	10
	2	$\frac{1}{16}$	225	192	9
	back	$\frac{1}{16}$	225	192	9

Table VIIIb.—Welding Procedures for Fillet Welds made by the Self-Adjusting Arc Process in Aluminium Plate (Waite[21]).
Preparation: Square Edge throughout. Fit up: No gap recommended but should not exceed $\frac{1}{4}$ of plate thickness.

Plate Thickness (in.)	Leg Length		Downhand and Horizontal			Vertical			Overhead		
	T-fillet (in.)	Lap (in.)	Welding Speed (in./min.)	Current (amp.)	Wire Feed (in./min.)	Welding Speed (in./min.)	Current (amp.)	Wire Feed (in./min.)	Welding Speed (in./min.)	Current (amp.)	Wire Feed (in./min.)
$\frac{1}{4}$	$\frac{5}{16}$	—	16	225	192	16	235	196	18	260	212
$\frac{1}{4}$	—	$\frac{1}{4}$	16	225	192	16	235	196	18	260	212
$\frac{3}{8}$	$\frac{1}{4}$	—	12	265	212	12	265	212	12	265	212
$\frac{3}{8}$	—	$\frac{3}{8}$	12	265	212	12	265	212	12	265	212
$\frac{1}{2}$	$\frac{5}{16}$	—	11	300	245	11	300	245	11	300	245
$\frac{1}{2}$	—	$\frac{1}{2}$	11	300	245	11	300	245	11	300	245
Arc length to be maintained at $\frac{3}{8}$ in. throughout.			Argon flow 40 cu. ft./hr.			Argon flow 70 cu. ft./hr.			Argon flow 70 cu. ft./hr.		

43 S wire gave strengths of 7·5 to 9·75 tons/sq. in. as welded, the failures occurring by shearing through the throat of the welds.

Applications

Typical applications involving the use of the self-adjusting arc process are described[9, 14, 24]. They include the fabrication by vertical butt welds of a large storage tank in 1 in. thick aluminium plate, the joining of the two halves of a cast aluminium space-heater and the production of metal window frames in the 61 S alloy. The process has also been used in the fabrication of structures such as air and acid vapour-filters and large vats[9]. In describing these applications, the authors give details of the various stages of fabrication and the welding conditions used.

The production of large tank-cars in plate of $\frac{1}{2}$ in. to $1\frac{1}{8}$ in. thickness is also considered in detail[14, 24]. The longitudinal seams in the main shell were completed by controlled-arc equipment in one pass from each side after back chipping. The heads were then fitted and the circumferential welds made by the same process after which the tank was completed by machine welding the dome to the top plate. The manufacture of aluminium truck-bodies of up to 20 tons capacity is also described[14]. The bodies were fabricated from sheet and extruded sections tack welded into the complete assembly and then seam welded. Controlled-arc welding has also been employed in the production of water-tight deck bulks for pontoon bridges. Two channels in the Dural type alloy 14 ST were jigged face to face and each seam welded, using aluminium wire at a welding speed of about 60 in. min.[24]

Another application for which the controlled-arc process has been found to be suitable, is in the rebuilding of worn ring grooves in Diesel pistons[9, 14]. After machining out the original grooves, the piston is preheated, and welded in a rotating fixture. The pistons are then slowly cooled under an asbestos blanket to minimise distortion. The mechanised process has also been applied to the welding of 16 s.w.g. sheet in the 3 S, 61 S and 75 S alloys using $\frac{1}{16}$ in. diameter 43 S filler wire. Welds were produced using both pure argon and oxy-argon at welding speeds of up to 190 in.min.[16]

Table IXa.—Tensile Strengths of Butt Welds made by Self-Adjusting Arc Process in Aluminium Alloy Plate in the Downhand Position (Muller, Gibson and Roper[9]).

Thick. & Comp. Plate (in.)	Edge Preparation	Wire (in.)	Passes	U.T.S. (ton/sq. in.)	Fracture
$\frac{1}{8}$, 2S	Square	$\frac{1}{16}$, 2S	2	5·8	Plate
$\frac{3}{16}$, 3S	Square	$\frac{1}{16}$, 2S	1	6·7	Plate
1, 3S	Double Vee	$\frac{1}{32}$, 2S	4	8·1	Weld
$\frac{3}{8}$, 61S	Square	$\frac{1}{16}$, 43S	2	12·9	Plate
$\frac{1}{4}$, 61S	Square	$\frac{1}{16}$, 43S	2	19·7*	Plate
$\frac{3}{4}$, 61S	30 deg. Vee	$\frac{1}{32}$, 43S	2	11·4	Plate
$\frac{3}{4}$, 61S	30 deg. Vee	$\frac{1}{32}$, 43S	2	17–18·7*	Weld

* Heat-Treatment: Solution treated at 520 deg. C. Aged 8 hrs. at 175 deg. C.

WELDING OF COPPER BASE ALLOYS

General Data

The welding of copper base alloys by the self-adjusting arc process has been considered in some detail[9, 11]. Satisfactory deposits have been made with electrode wire of aluminium-bronze, silicon-bronze, deoxidised copper, phosphor tin bronze, leaded phosphor-tin bronze and cupro-nickel. Alloys with a zinc content exceeding 0·5 per cent. are difficult to use as electrode material due to zinc vaporization which causes excessive spatter, poor coalescence and unsatisfactory

Table IXb.—Mechanical Properties of Self-Adjusting Arc Butt Welds in Aluminium Alloy Plate using a Special High-Speed Multi-Run Technique (Houldcroft[25]).

Plate Thick. and Comp. (in.)	Edge Preparation	Welding Position	Passes	U.T.S. (ton/ sq. in.)	Elong. (per cent. on 2 in.)	Fracture
¼, 61 S	60 deg. Vee	Groove-O	3	14·0	5·0	Plate
		Back-D	3			
¼, 61 S	60 deg. Vee	Groove-V	5	14·7	3·5	Plate
		Back-V	3			
¼, 61 S	60 deg. Vee	Groove-H	3	14·3	5·0	Plate
		Back-H	3			
⅜, 61 S	Double 60 deg. Vee	Groove-O	3	15·6	2·5	Weld or Plate
		Back-D	4			
⅜, 61 S	Double 60 deg. Vee	Groove-V	3	13·75	7·0	Plate
		Back-V	2			
⅜, 61 S	Double 60 deg. Vee	Groove-H	3	14·5	4·5	Plate
		Back-H	3			
⅜, 52 S	Double 60 deg. Vee	Groove-O	3	15·3	10·0	Plate
		Back-D	4			
⅜, 52 S	Double 60 deg. Vee	Groove-V	3	14·9	2·0	Weld
		Back-V	3			
⅜, 52 S	Double 60 deg. Vee	Groove-H	4	15·2	6·0	Plate
		Back-H	4			

NOTE: (1) 43 S filler wire used throughout; (2) All welds back-chipped; (3) D—Downhand, O—Overhead, V—Vertical, H—Horizontal.

fusion with the base material. Excellent porous free deposits may be obtained with silicon and aluminium-bronzes while sound weld metal can be produced with deoxidised copper at currents about double those used for silicon and aluminium-bronzes. Deposits of deoxidised copper made at lower currents are usually found to contain porosity due to the chilling action of the base metal. Porosity with this material can also be prevented by preheating. Preheating is also advantageous in obtaining sound deposits in the phosphor-bronzes although for bearing overlays porosity may not be objectionable[11]. No details are given of the characteristics of deposits made with cupro-nickel wire.

The majority of the available information concerns depositions made with aluminium-bronze wire. Both α and $\alpha\beta$ types have been used for overlay and joining purposes. Welds have been made in aluminium-bronze, carbon steel and propeller-type bronze materials while bearing overlays have been applied to mild steel, grey cast iron, deoxidised copper, naval brass and manganese-bronze[9, 11].

Argon is preferred as the shielding gas for most copper alloys since with suitable welding conditions the arc is smoother, more stable and more free from spatter than when helium is used[9, 11]. Better results are said to be obtained however, when the latter gas is used for welding copper as the higher currents required appreciably reduce spatter and the higher heat-input available assists penetration and enables faster welding speeds to be reached[11]. With all materials the removal of heavy oxide and scale is advised to ensure coalescence of the deposit and adequate fusion with the base material, particularly where overlays are involved.

A family of curves showing the relationship between burn-off rate and arc voltage at constant current for $\frac{1}{16}$ in. diameter aluminium-bronze wire is given in Fig. 12. Typical welding conditions for various thicknesses of aluminium-bronze and steel plate using aluminium-bronze filler wire are included in Table X. Satisfactory deposits can be made employing either forehand or backhand techniques. The shallower penetration produced by the latter technique is an advantage in applications where base metal alloying requires to be minimised.

Comprehensive data relating to the mechanical properties of butt welds together with details of edge preparation, pass sequence and welding conditions are reported[11]. The

Table X.—Conditions for Self-Adjusting Arc Welding of Aluminium-Bronze and Steel Plate with Aluminium-Bronze Wire (Robinson and Berrymann[11]).

Plate Thickness (in.)	Position	Wire Diameter (in.)	Current (amp.)
$\frac{1}{8}$	D, H, O, VD	$\frac{5}{64}$	110–120
$\frac{3}{16}$	D, H, O, VD	$\frac{5}{64}$	110–180
$\frac{1}{4}$	OH, V	$\frac{5}{64}$	110–140
$\frac{1}{4}$	D, VD, H, O	$\frac{5}{64}$	170–190
$\frac{1}{4}$	D, H	$\frac{1}{16}$	190–310
$\frac{3}{8}$	D, H	$\frac{1}{16}$	280–350
$\frac{3}{8}$	V, O	$\frac{5}{64}$	110–200
$\frac{1}{2}$	D, H	$\frac{1}{16}$	280–350
$\frac{1}{2}$	V, O	$\frac{5}{64}$	140–210

NOTE: Silicon bronze wire requires 10–30 per cent. less current, due to high fluidity of deposited metal. Cold copper plate, due to high thermal conductivity, requires about 100 per cent. more current with a correspondingly larger wire size.

D—Downhand H—Horizontal O—Overhead V—Vertical up VD—Vertical down

welds involved were $\frac{3}{8}$ in., $\frac{1}{2}$ in. and $\frac{3}{4}$ in. thick silicon and aluminium-bronzes, $1\frac{1}{2}$ in. thick manganese-bronze casting using aluminium-bronze filler, $\frac{1}{4}$ in. thick deoxidised copper welded with both copper and silicon-bronze wire and $\frac{3}{8}$ in. and $\frac{3}{4}$ in. thick mild steel welded with aluminium-bronze. The properties investigated were tensile strength, ductility and Charpy impact values at room and sub-zero temperatures. A synopsis of some of the results are given in Table XI. A metallographic examination of welds in the various materials was carried out.

Applications

Examples and illustrations of typical applications of the two processes to the welding of various components with aluminium-bronze are given [10, 11]. Satisfactory overlays in this material have been applied to heavy-duty valves and compressors, and welds in dissimilar metals, e.g. silicon-bronze baffle plates to a steel body have been produced showing excellent properties[10, 11].

The fabrication of a silicon-bronze agitator arm involving the welding of $\frac{3}{8}$ in. thick silicon-bronze plate to a casting in the same alloy is described[11]. Another application for

Table XI.—Summary of Mechanical Properties from Butt Welds in Various Copper Base Alloys and Mild Steel Plate (Robinson and Berryman[11]).

Plate	Wire (in.)	Nominal Plate Composition	Plate Thickness (in.)	Nominal Wire Composition	Type of Test-piece	U.T.S. (ton/sq. in.)	Elongation (per cent. on 2 in.)	Position of Fracture	Bend
Al Bronze	$\frac{1}{16}$ Al Bronze	7 per cent. Al, 2 per cent. Fe.	$\frac{3}{8}$	7 per cent. Al, 2 per cent. Fe.	Transverse tensile	34·0	34·5	In weld	Guided 180 deg.
Al Bronze	$\frac{1}{16}$ Al Bronze	7 per cent. Al, 2 per cent. Fe.	$\frac{3}{8}$	9·5 per cent. Al, 0·75 per cent. Fe.	Transverse Tensile	34·5	39·0	Edge of weld metal	Guided 180 deg.
Al Bronze	$\frac{1}{16}$ Al Bronze	7 per cent. Al, 2 per cent. Fe.	$\frac{3}{8}$	8·0 per cent. Al, 0·5 per cent. Fe max.	Transverse tensile	28·5	21·0	In weld	Guided 180 deg.
Al Bronze	$\frac{1}{16}$ Al Bronze	5 per cent. Al, 0·5 per cent. Fe max.	$\frac{3}{8}$	5 per cent. Al, 0·5 per cent. Fe max.	Transverse tensile	19·25	24·0	In weld	Guided 180 deg.
Al Bronze	$\frac{1}{16}$ Al Bronze	9·5 per cent. Al, 2·5 per cent. Fe, 1·0 per cent. Mn, 5·0 per cent. Ni.	$\frac{3}{8}$	9·5 per cent. Al, 0·75 per cent. Fe.	Transverse tensile	43·0	28·0	In weld	Guided 35 deg.
Silicon Bronze	$\frac{1}{16}$ Si Bronze	3·0 per cent. Si, 1·0 per cent. Mn.	$\frac{3}{8}$	3·0 per cent. Si, 1·0 per cent. Mn.	Transverse tensile	23·5	45·0	In weld	Guided 180 deg.
Silicon Bronze	$\frac{1}{16}$ Silicon Bronze	3·0 per cent. Si, 1·0 per cent. Mn.	$\frac{3}{4}$	3·0 per cent. Si, 1·0 per cent. Mn.	All weld metal (0·505 in.)	23·5	54·0	—	—
Manganese Bronze	$\frac{1}{16}$ Aluminium Bronze	1·0 per cent. Al, 1·0 per cent. Fe, 1·5 percent. Mn, max. 55–60 per cent. Cu Zn Bal.	$1\frac{1}{2}$ casting	9·5 per cent. Al, 0·75 per cent. Fe.	All weld metal (0·505 in.)	36·0 top 35·0 bottom	31·0 21·0	—	—
Manganese Bronze	$\frac{1}{16}$ Aluminium Bronze	1·0 per cent. Al, 1·0 per cent. Fe, 1·5 per cent. Mn, max. 55–60 per cent. Cu Zn Bal.	$1\frac{1}{2}$ casting	9·5 per cent. Al, 0·75 per cent. Fe.	Transverse tensile	28·0	9·5	Edge of weld metal	—
Manganese Bronze	$\frac{1}{16}$ Aluminium Bronze	1·0 per cent. Al, 1·0 per cent. Fe, 1·5 per cent. Mn, max. 55–60 per cent. Cu Zn Bal.	$1\frac{1}{2}$ casting	8 per cent. Al, 0·5 per cent. Fe max.	All weld metal (0·505 in.)	20·5 top 12·0 bottom	36·0 12·5	—	—
Manganese Bronze	$\frac{1}{16}$ Aluminium Bronze	1·0 per cent. Al, 1·0 per cent. Fe, 1·5 per cent. Mn, max. 55–60 per cent. Cu Zn Bal.	$1\frac{1}{2}$ casting	8 per cent. Al, 0·5 per cent. Fe max.	Transverse tensile	20·5	—	—	—
Mild Steel	$\frac{1}{16}$ Al Bronze	—	$\frac{3}{8}$	9·5 per cent. Al, 0·75 per cent. Fe.	Transverse tensile	29·5	—	Parent plate	Guided 180 deg.
Mild Steel	$\frac{1}{16}$ Al Bronze	—	$\frac{3}{4}$	9·5 per cent. Al, 0·75 per cent. Fe.	All weld metal (0·505 in.)	46·5	20·0	—	—
Mild Steel	$\frac{1}{16}$ Al Bronze	—	$\frac{3}{4}$	8·0 per cent. Al, 0·5 per cent. Fe max.	All weld metal (0·505 in.)	31·5	28·5	—	—
Deoxidised Copper	$\frac{1}{16}$ Deoxidised Copper	—	$\frac{1}{4}$	—	Transverse tensile	13·5	28·0	Edge of weld metal	Free 180 deg.
Deoxidised Copper	$\frac{1}{16}$ Silicon Bronze	—	$\frac{1}{4}$	3·0 per cent. Si, 1·0 per cent. Mn.	Transverse tensile	13·25	37·0	Edge of weld metal	Free 180 deg.

(*Table XI contd. over page*)

Table XI contd.

Plate	Wire (in.)	Nominal Plate Composition	Plate Thickness (in.)	Nominal Wire Composition	Type of Testpiece	U.T.S. (ton/sq. in.)	Elongation (per cent. on 2 in.)	Position of Fracture	Bend
Electrolytic Tough Pitch Copper	$\frac{3}{32}$ Deoxidised Copper	—	$\frac{1}{4}$	—	Transverse tensile	11·75	25·0	Edge of weld metal	Free 180 deg.

which silicon-bronze welding has been suitable, is in the production of hot water storage heaters of various sizes. A detailed account with illustrations is given of the sequence of operations involved in producing these vessels. Specific cases where the process has been used successfully for repair work are reported. These include the resurfacing of rolling mill guides in phosphor-bronze or aluminium-bronze with either a similar type of phosphor-bronze or aluminium-bronze and the repair of copper tuyères and marine propellers[12]. The techniques employed in the welding of laminated to solid copper bus-bars has also been described[24].

WELDING OF MAGNESIUM ALLOYS

Work on the welding of magnesium by the self-adjusting arc process is the subject of a paper by Klain[17].

Details are given of mechanical properties and welding conditions for welds made in plate of composition Al 0·3 per cent., Zn 0·1 per cent., Mn 0·3 per cent., using wire containing 6·0 per cent. Al, 1·0 per cent. Zn, and 0·3 per cent. Mn. The arc could be established by either a scratching technique, or by point contact and the wire feed could begin either before or after the arc was struck. With high wire-feed speeds however, it was better to have the wire feeding before striking the arc if " burn-backs " were to be avoided. Another cause of " burn-backs " was the use of wire having a heavy oxide coating which induced shorting inside the guide tube and interfered with the smoothness of the wire feed. The author states that no special cleaning is required if the wire initially was reasonably clean, but deterioration sufficient to produce frequent " burn-backs " occurred when wire was exposed to ordinary shop atmosphere for several weeks.

The paper includes a comprehensive table of operating conditions for $\frac{1}{16}$ in. wire, including details of welding currents, burn-off rates, arc voltages and welding speeds for arcs in argon and helium. The threshold currents for $\frac{1}{16}$ in. and $\frac{3}{32}$ in. diameter wires of this alloy are given in Table II, while a burn-off rate curve for the thinner wire is included in Fig. 7. Details are given of the welding conditions employed for making butt and fillet welds in $\frac{1}{4}$ in., $\frac{1}{2}$ in. and 1 in. thick plate and typical examples are illustrated to show the general appearance of the welds, weld contours and depth of penetration in fillets. The tensile strengths of transverse test-pieces machined from butt welds in each thickness of plate gave joint efficiencies of from 80 per cent. to 98 per cent. with fractures occurring mainly in the parent plate. Guided face, root and side bend tests carried out on welds in $\frac{1}{2}$ in. and 1 in. thick material withstood 90–120 deg. before failure occurred.

Visual examination of fractured surfaces and radiographic examination of the welds showed no porosity although on microscopical examination a slight amount of porosity was found in multi-pass welds. This, however, was thought to be due to incipient fusion of a Mg-Al compound when reheating occurred from subsequent passes.

WELDING OF CARBON STEELS

The welding of carbon steels by the self-adjusting arc process is the subject of a paper by Herbst and McElrath[22]. It is stated that unsatisfactory results were obtained when commonly used inert gases were employed. Poor bead contours, porosity, undercutting and high spatter rate were prevalent while welding speeds were slow and welding costs high. Marked improvements, however, were obtained when argon containing about 5 per cent. oxygen was used. Welding could be carried out at high welding speeds, and no undercutting was encountered while the arc showed good stability and a low spatter rate. In addition, the frequency of metal transfer is reported as being 30 to 50 times higher than in a pure argon atmosphere, thus enabling a spray type transfer to be established at much lower current densities.

With oxygen-containing argon, it is also possible to weld satisfactorily with straight polarity. For information, curves have been reproduced in Figs. 7, 11, 13 and 15, showing burn-off rates for wire of various sizes operating with each electrode arrangement in either argon or oxy-argon.

The process finds its greatest application for welding plate of $\frac{3}{16}$ in. thickness and over. A Vee-type edge preparation is recommended for thicknesses in the range of $\frac{3}{16}$ in. to $\frac{3}{4}$ in., while for heavier plates " U " grooves may be preferred. The process is applicable to low-alloy steels and to killed or semi-killed materials, but porosity may be encountered in rimming steels.

To obtain sound welds in killed, semi-killed and rimmed plate, the welding wire should contain deoxidising elements. The use of rimming quality wire usually produces deposits containing gross porosity.

The authors report that the process has shown promising results for welding steels subject to hard-zone cracking, and attribute this to the exclusion of hydrogen[22]. With wire containing less than 0·10 per cent. carbon, there is no loss of carbon during welding, but where the carbon content of the wire is in the region of 0·30 per cent. a loss of 15 to 20 per cent. may occur.

The incidence of porosity in the weld metal is affected by a number of factors which include gas flow, arc voltage, current density and welding speed. Using oxy-argon as the shielding gas, the authors found that the minimum gas flow for producing sound welds was 40 cu. ft./hr. The effectiveness of the shielding atmosphere may be lost when the electrode wire and arc are not concentric with the gas pattern, and these conditions may result in porous welds. With good gas shielding, the incidence of porosity is not affected by arc voltages of 24 to 32 volts, but porosity may occur with lower arc voltages. Using wires varying from $\frac{3}{64}$ in. to $\frac{3}{16}$ in. diameter there was a greater tendency for porous deposits to be produced with the thinnest gauge while no porosity was encountered with wire exceeding $\frac{1}{16}$ in. diameter. The speed of welding was also found to have an effect on the incidence of porosity, and a series of tests was made at welding speeds ranging from 5 to 35 in. per minute. With the conditions and type of test employed, no porosity was apparent at welding speeds up to 15 in./min. but at the higher speeds porous welds were encountered. The authors also give details of the effect of arc voltage, and current density on penetration.

Data are given relating to both self-adjusting and controlled

Table XII.—Typical Welding Conditions for Austenitic Stainless Steels (Muller, Gibson and Roper[9]).

Plate Thickness (in.)	Welding Position	Wire Diameter (in.)	Shielding Gas	Gas Flow (cu. ft./hr.)	Current Range (amp.)	Wire Feed Range (in./min.)	Deposition Rate (lb./arc/hr.)
$\frac{1}{8}$–$\frac{1}{4}$	all	0·035	He	20–30	110–150	220–310	3·7– 5·2
$\frac{1}{4}$–1·0	V and O	0·035	A	20–30	110–140	220–260	3·7– 4·3
$\frac{1}{2}$–1·0	V and O	0·045	A	20–30	140–180	150–200	4·1– 5·3
$\frac{3}{16}$–$\frac{3}{8}$	D and H	0·045	A	30–40	190–310	210–440	5·7–11·8
$\frac{1}{4}$ and over	D and H	0·062	A	30–40	280–350	240–330	12·6–17·3

D = Downhand. H = Horizontal. V = Vertical. O = Overhead.

arc processes showing welding conditions suitable for butt and fillet welds in various thicknesses of plate. Typical forms of edge preparation, and the number of passes required are also indicated. The authors emphasise the importance of avoiding very short arc lengths, and recommend arc lengths of $\frac{3}{16}$ in. to $\frac{1}{4}$ in. as being suitable. With excessive arc lengths, little penetration was obtained and it was difficult to direct the arc effectively. " Arc blow " should be prevented as this creates disturbances in the gas stream which upset the shielding action.

For root passes, the torch should be manipulated with a slight backward and forward motion to promote coalescence and to give a good bead contour. With finishing passes slight weaving may be used, but where excessive weaving would be required to complete the weld, multiple stringer beads are preferred. Shorter arc lengths should be employed on root passes than for finishing passes.

A comparison is given of the mechanical properties obtained on mild steel deposits produced by the self-adjusting arc process with those obtained from covered electrodes. From the data given, there appears to be no significant differences in properties obtained with either method of welding.

WELDING OF STAINLESS STEELS

General Data

The welding of these materials has been dealt with in general terms by Muller, Gibson and Roper[9]. They report that all types of austenitic stainless steels can be welded satisfactorily by these processes using argon or helium as the shielding gas. Wire of 0·062 in., 0·045 in. and 0·035 in. diameter are used, the former being for downhand welding and the thinner gauges for positional work. The minimum plate thickness which can be welded is about $\frac{1}{8}$ in. Typical welding conditions for various thicknesses of plate are given, together with details of gas flows and deposition rates. These data are reproduced in Table XII. Filler wire compositions are nominally the same as the parent material although a closer control of analysis is necessary to avoid cracking during cooling. There is normally no loss of alloying elements during welding with the exception of titanium of which 15–40 per cent .of that originally present is lost. To show these high recovery values the paper includes results of analyses obtained from samples of wire and weld metal deposits. There is normally no trouble from porosity when welding stainless steel although it may be encountered with poor arc conditions and inadequate gas shielding.

The use of oxy-argon as the shielding medium is discussed by Breymeier[23] and Rockefeller[24]. Improved metal transfer characteristics are claimed and it is possible to weld at higher speeds and lower currents. With this gas, the process will operate satisfactorily with either electrode positive or negative. Fig. 6 shows the effect of the use of argon and oxy-argon on bead continuity at high welding speeds. Burn-off rate curves for stainless steel are reproduced in Figs. 7 and 16.

The results of a comprehensive investigation of the mechanical properties and corrosion resistance of welded joints and weld deposits are reported by Benz and Sohn[19]. The properties obtained compare favourably with those exhibited by welds made with covered electrodes of the same composition. The types of plate and filler wire used for the tests are given in Table XIII. Tensile strengths exceeding 35 tons/sq. in. with elongation values ranging from 30 to 40 per cent. were obtained on weld metal test-pieces from the six types of steel while similar results with somewhat higher ductility were obtained from transverse tests machined from butt welds. Typical results are given in Table XIV. Transverse guided bend tests prepared from butt welds in $\frac{1}{2}$ in. thick plate, all withstood 180 deg. bend without cracking. The results of Charpy impact tests carried out at room temperature and at various sub-zero temperatures down to about —195

Table XIV.—Mechanical Properties of Transverse Test Pieces Machined from Butt Welds in $\frac{1}{2}$ in. thick Stainless Steel Plate in the As-Welded Condition (Benz and Sohn[19]).

Parent Plate A.I.S.I. Type	Filler Metal A.I.S.I. Type	Ultimate Tensile Strength (ton/sq. in.)	Elongation (per cent. on 2 in.)	Location of Fracture
304 ELC	308 ELC	37·5	63·3	Weld
304	308	38·5	51·0	Plate
310	310	34·5	40·8	Plate
316	316	38·0	45·7	Usually Plate
321	321	36·0	57·7	Plate
347	347	39·0	50·5	Usually Plate

Table XIII.—Grades of Austenitic Stainless Steel Plate and Filler Wire Used for Investigation of Mechanical Properties and Corrosion Resistance (Benz and Sohn [19]).

Plate (A.I.S.I. Specification)	Filler Wire (A.I.S.I. Specification)	Similar British Specification	Nominal Composition
304 ELC	308 ELC	—	0·03 per cent. C, 18 per cent. Cr, 8 per cent. Ni.
304	308	B.S. 1449 En 58 E	18 per cent. Cr, 8 per cent. Ni.
310	310	D.T.D. 493	25 per cent. Cr, 20 per cent. Ni.
316	316	B.S. 1449 En 58 H and J	18 per cent. Cr, 10 per cent. Ni, Mo.
321	321	B.S. 1449 En 58 B and C	18 per cent. Cr, 8 per cent. Ni, Ti.
347	347	B.S. 1449 En 58 F and G	18 per cent. Cr, 8 per cent. Ni, Cb.

deg. C. show little difference from those obtained from welds made with standard covered electrodes.

Corrosion tests were carried out on all weld metal and butt weld specimens in the as welded condition and in various conditions of heat treatment. Two corrosive media were used, namely, boiling 65 per cent. nitric acid and boiling 1:8 copper sulphate-sulphuric acid solution. From the data obtained the authors conclude that the corrosion resistance of deposits involved are similar to those of covered electrodes.

Applications

The fabrication of pressure vessels for containing fuming nitric acid under 1,500 lb. pressure at about 350 deg. C. is described[18]. The vessels were produced in 1 in. thick Type 347 material using $\frac{1}{16}$ in. diameter wire of the same composition. The shell plates having a vee edge preparation, were first welded from one side, then back-chipped and finished with a final run on the reverse side. The construction of refinery and pressure vessels in $\frac{1}{4}$ in. thick material is also described.

The procedure for fabricating stainless steel pipe of up to 1 in. thickness by controlled-arc welding is reported with details of welding conditions and edge preparation employed[24]. This process has also been used for welding sheet of 0·025 in. thickness for aircraft purposes at a speed of about 250 in. min. with oxy-argon as the shielding gas[16].

WELDING OF HEAT-RESISTING ALLOYS

Work on the welding of one specific material is mentioned by Muller, Gibson and Roper[9]. The nominal composition of the plate was 0·50 per cent. C, 20 per cent. Cr, 20 per cent. Ni, 20 per cent. Co, 4 per cent Mo, 4 per cent. W, 4 per cent. Cb, 0·60 per cent. Mn, and 0·2 per cent. Si. The plate, of 1 in. in thickness, was welded in five passes using 0·078 in. diameter, wire of the same composition, the edge preparation consisting of a "U" groove with a $\frac{1}{8}$ in. root face. Welding was carried out without preheat over a copper backing strip with a length of silica tape located between the backing bar and the plate. A welding current of about 350 amp. was used with an argon flow of 60 cu. ft. per hour.

WELDING OF CLAD STEELS

Procedures for welding nickel-clad and stainless-clad steels by the controlled-arc process are described by Watson and Rothermel[12]. The gas used was chiefly argon, although the authors report that the arc was more stable with a 90 per cent. argon–10 per cent. helium mixture. They also comment on the importance of cleaning the plate edges prior to welding, and the necessity for efficient gas shielding if sound crack-free deposits are to be obtained. More adequate gas coverage was provided if an extra shroud was attached to the barrel of the welding head.

Nickel-Clad Steels

Welding tests were carried out on plates with 10 per cent. and 20 per cent. cladding in thicknesses ranging from $\frac{1}{4}$ in to $\frac{3}{4}$ in. A square edge preparation was used for $\frac{1}{4}$ in. and $\frac{3}{8}$ in. thick material, the weld being completed in two passes with No. 61 nickel* wire. The first pass aimed at obtaining penetration from the unclad side to the interface of the cladding, the weld being then completed by a deposit on the cladding. With thicker plates, a bevelled joint preparation was used and the steel side was welded manually with mild steel electrodes. The clad side was then back-chipped and finished by a run of nickel. The authors include details of welding conditions used for these tests. The ductility of the joints was assessed by free and side bend tests, the resultant elongation figures obtained on the former being 35–50 per cent. on the steel side and 30–40 per cent. on the clad side. Analyses of the top layer of the final bead showed an iron content of 5–7 per cent. but contamination with iron could be reduced to 3–4 per cent. when the weld on the clad side was completed with three passes. It was also possible to produce satisfactory single-pass welds in $\frac{3}{8}$ in. thick plate welding from the carbon steel side with No. 61 nickel wire. Subsequent bend tests gave 35–50 per cent. elongation on the steel side, while the clad side bent through 180 deg.

Stainless-Clad Steels

Austenitic Type Cladding

Test welds were made on plate of $\frac{3}{8}$ in. to $\frac{3}{4}$ in. thickness having coatings of Type 304 (18–8) and Type 347 (18–12–Cb) stainless steel. In one series, welds were completed in two passes the initial run being on the carbon steel side. Both 25 Cr–20 Ni and 19 Cr–9 Ni types of electrode wire were used and each succeeded in producing welds of good ductility. Single-pass welds deposited from the carbon steel side were prepared on Type 304 clad material. Low ductility values were obtained when 19 Cr–9 Ni wire was used, but more satisfactory results were shown with 25 Cr–20 Ni wire. With the former type of deposit, it was found that considerable hardening had occurred in the welds on the steel side which was not apparent with the 25 Cr–20 Ni deposit.

Martensitic Type Cladding

The parent plate was $\frac{3}{4}$ in. thick clad with Type 410 (12 per cent. Cr air-hardening) steel and welds completed in one pass were deposited using 25 Cr–20 Ni wire. In the as-welded condition bend tests showed little ductility on the clad side but a 180 deg. bend was obtained after stress-relieving at about 630 deg. C. The lack of ductility in the as-welded condition was due to the hardening produced in the cladding alloy.

Applications

Yaczko[18] describes in detail the manufacture of refinery vessels in stainless-clad plate involving self-adjusting arc welding. The edges of the plate forming the shell were prepared by flame cutting to give a 60 deg. vee on the steel side and then welded by submerged arc. The clad side was then back-chipped and the weld completed by self-adjusting arc with stainless steel wire.

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Figs. 1 to 3, are by courtesy of Air Reduction Co. and Figs. 4 to 6 are reproduced by courtesy of The Welding Journal.

* Composition[15]; 2·3 per cent. Ti, 0·9 per cent. Al, 0·6 per cent. Fe, 0·6 per cent. Si, 0·04 per cent. C, Bal, Ni.

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IMPACT TORSION TESTING OF BOLT WELDS

Examination of the metallurgical structures of bolt welds made under various welding conditions had suggested that the normal methods of testing the strength of the welds were insufficiently discriminating between the various structural conditions present, i.e. a fully "fused" weld or "solid phase" weld. The interesting method of impact-torsion testing was therefore employed to investigate more fully the possibility of differences in strength.

By H. E. DIXON, M.Sc., A.I.M., and J. E. ROBERTS, M.Eng., A.I.M.

INTRODUCTION

In the course of work on resistance welding of cold-headed bolts to mild-steel sheet, difficulties were encountered in testing of high-strength welds by static methods of torsion and tension. In addition, no differences could be detected between welds where the metal had been molten at some stage, i.e. a fused weld, and welds made in the solid phase by interfacial crystal growth, i.e. a pressure weld. A search was therefore made for a more discriminating method of testing the bolt welds, which would still be rapid and simple. Normal impact testing using a swinging pendulum type of machine was not satisfactory, as it was impossible to break welds of any reasonable static strength, failure being by bending of the bolt shank. The suggestion was then made that impact torsion might give the desired information, as the impact could be applied nearly in the plane of the weld, and failure would almost certainly occur by torsional shear of the weld itself. The details of the tests made are given in this report.

METHOD OF TESTING

The impact torsion machine used, was one constructed by the Armaments Research Establishment, Woolwich Arsenal, and was made available to the B.W.R.A. for the tests.

Bolts welded to 3 in. by 2 in. by 12 s.w.g. plate were tested, the specimen being held in a special adapter, one half of which fits over the bolt shank, and has a hexagonal collet which is tightened on the bolt head. The other part of the adapter has two steel pins which engage in the locating holes of the plate and it is held to the plate by two small screws (these are simply to hold the plate, the torsional load when the impact takes place being carried by the steel pins). The adapters are specially shaped to be held in the grips of the testing machine. One end is held in a clamp which has a movement of approximately $\frac{1}{8}$ in. parallel to the bolt shank, and the other end is clamped to a light double cantilever beam. This beam is so arranged that with the sliding clamp withdrawn, it is quite clear of the two pins which project from the face of a flywheel, the axis of which is the same as the axis of the bolt. The flywheel is driven through a clutch by an electric motor. It is accelerated to greater than 750 r.p.m. and the drive is disengaged. When the speed of the flywheel, running free, falls to 750 r.p.m. a lever is depressed which starts a stopwatch, and simultaneously projects the specimen forward so that the beam engages with the pins on the flywheel. The pins supply the torsional impact for breaking the specimen, and the flywheel rapidly decelerates, the rate of deceleration depending on the energy absorbed in breaking the specimen. When the speed is falling steadily, the lever is again depressed, and the time to fall to a certain speed is thus obtained. From this, knowing the deceleration due to friction, windage, etc., of the flywheel when running free with no impact, the energy absorbed by the impact can be calculated.

A diagram of the machine and adapters is shown in Fig. 1.

PRELIMINARY TESTS

An initial series of welds was made under conditions which would produce both fused welds and pressure welds of fairly low and of high static-torsion strengths, and welds which

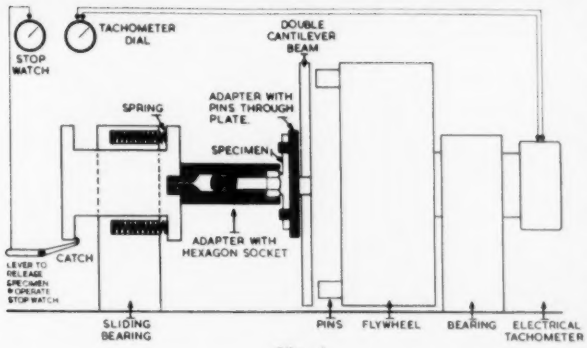

Fig. 1

were rapidly cooled and others which cooled comparatively slowly (conditions obtained by altering the time of electrode dwell). The groups consisted of eight welds, of which six were tested by impact torsion, one by static torsion, and one sectioned to determine the structure present. The test results are shown in Table I.

Table I.—Impact-Torsion Testing of Welds of $\frac{1}{16}$ in. diameter Bolts to 12 s.w.g. Plate

Specimen (No.)	Static Torsion Strength (lb.-ft.)	Weld Structure	Mean Impact Torsion (ft.-lb.)	Coefficient of Variation
1–8	45	Fused weld.	50	6·3
9–16	65	Pressure weld.	50	14·1
17–24	75	Small fused weld.	20	16·7
25–32	90	Fused weld.	Welds too large to break.	
33–40	40	Pressure weld.	26	10·0
41–45	75	Pressure weld	53	14·3
49–56	70	Small fused zone in sheet.	Hexagon of head stripped.	
57–64	45	Pressure weld.	22	23·7

The results indicated that the impact torsion strength was generally lower than the static-torsion strength, and in one case (Specimen Nos. 17–24) the difference was very great. These differences, however, did not appear to depend on the type of structure present, or on the static strength. Therefore it was decided to carry out a second series of tests where larger numbers of specimens would be available, both for impact and static strengths, and for sectioning.

MAIN SERIES

The adapter used in the preliminary series had a simple hexagon socket, and slipping was experienced where the weld strengths were high. Therefore, for the main series of welds, it was modified to provide a hexagon collet which could be tightened down on to the bolt head to give a more definite grip. This modification achieved the desired result and the only troubles which occurred in testing the main series were probably due to misalignment of the specimen in the testing machine.

The series consisted of five groups of welds designed to give fused and pressure welds of high (70 lb.-ft.) and low (40 lb.-ft.) static strengths. In each group thirty welds were made and of these fifteen were tested by impact torsion, and ten by static torsion. The remaining five were sectioned. By this means a good average value was obtained for all three properties of the welds.

The welding conditions and properties of the welds are given in Table II. Photo-macrographs of typical weld sections for each group are shown in Figs. 2–6 inclusive.

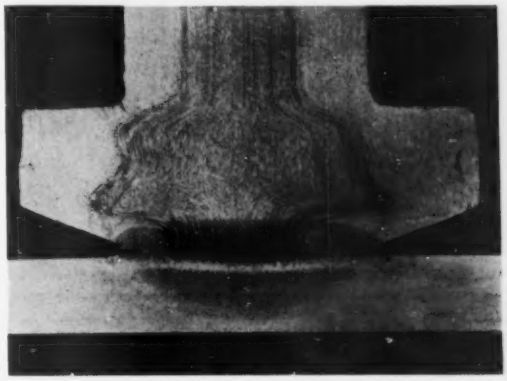

Fig. 2. Photomacrograph of weld, main series, group 1.

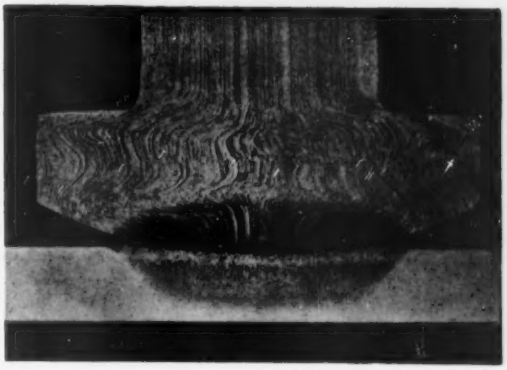

Fig. 3. Photomacrograph of weld, main series, group 2.

Table II.—Welding Conditions and Test Results for Main Series of Welds.

Group (Nos.)	Electrode Load (lb.)	Head Radius (in.)	Welding Current (kA)	Welding Time (Cycles, 50 c/s)	Structure	Static Strength			Impact Strength			Ratio I/S (per cent.)
						Mean, S. (lb.-ft.)	Standard Deviation (σ_S)	Coefficient of Variation	Mean, I. (ft.-lb.)	Standard Deviation (σ_I)	Coefficient of Variation	
1	1,500	0·625	12·9	5	P	45	1·0	5·3	33	5·2	15·6	73
2	1,750	0·625	12·6	10	P	68	2·5	3·7	53	6·8	13·0	78
3	1,000	0·625	13·2	10	F	68	4·7	6·9	58	4·6	7·9	85
4	1,000	1·25	13·9	10	F	67	4·2	6·3	55	8·6	15·7	82
5	1,000	0·625	13·8	10	F	68	3·9	5·7	55	3·9	7·0	81

P = Pressure Weld. F = Fused Weld.

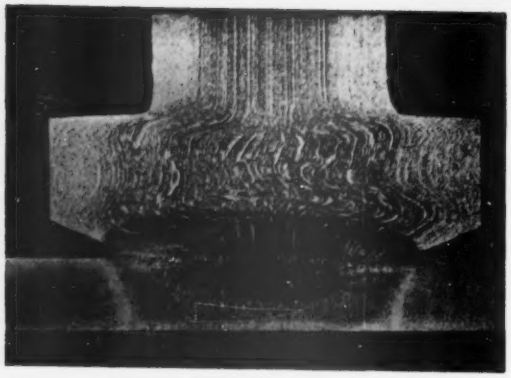

Fig. 4. Photomacrograph of weld, main series, group 3.

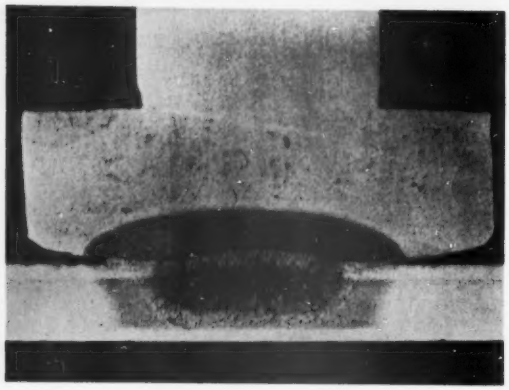

Fig. 5. Photomacrograph of weld, main series, group 4.

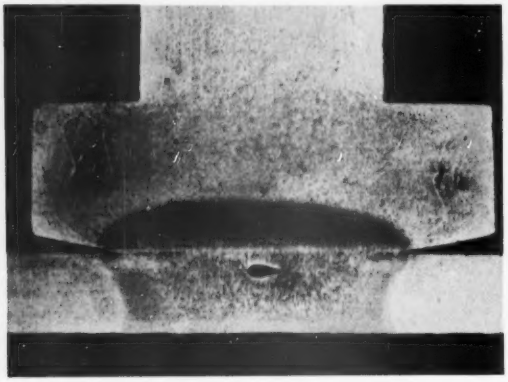

Fig. 6. Photomacrograph of weld, main series, group 5.

DISCUSSION OF RESULTS

The results of the main series show that the impact-torsion strengths are lower than the static-torsion values. The reduction tends to be rather greater in the case of a pressure weld, when shown as the ratio of impact to static strengths, this being 78 per cent. for the welds of Group 2, and 85 per cent., 82 per cent. and 81 per cent. for Groups 3, 4 and 5 respectively. All these four groups have sensibly the same average static strength, and though the mean impact strengths vary somewhat there is no significant difference between any of the four groups. The percentage fall for the low-strength group is slightly greater.

The direct comparison of the strengths obtained by the two methods is not strictly correct, as the static strengths are

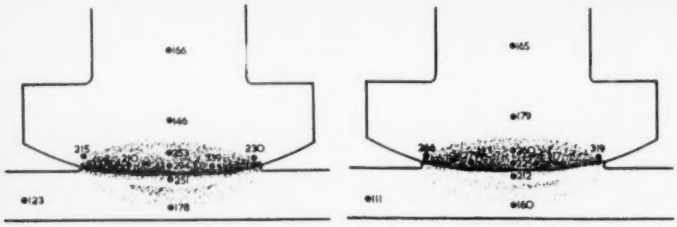

Fig. 7.

measured in terms of a torsional loading in pounds-feet, whereas the impact strengths are a measure of the absorbtion of energy in foot-pounds to produce fracture. A truer comparison is obtained by considering the ratios of the static strengths produced by welding under various conditions, and the ratios of the corresponding impact tests. Taking the lowest strength as the standard of comparison, the ratios are:

Group No.	Static Strength	Impact Strength
1	1·0	1
2	1·5	1·6
3	1·5	1·8
4	1·5	1·7
5	1·5	1·7

Thus the impact strength of the low-static-strength weld is relatively less than that of the high-static-strength welds, i.e the same conclusion as obtained by the direct comparison.

There was one case in Group 2 (Specimen No. 77) of an exceptionally low impact-strength in a group of high-strength welds. This was sectioned, along with another of the same group (Specimen No. 89) which had given a higher impact-strength. The appearance of the two welds was similar, though in No. 77 there were marked flow lines in the head of the bolt, whereas No. 89 had a fine-grained structure throughout the bolt (it is possible that they were from different batches of bolts). However, flow lines were observed in many of the other welds sectioned (see Figs.) and there is no reason for supposing No. 77 to be the only one of the impact-tested specimens to have such a structure, i.e. it is not thought that this difference can explain the low strength obtained.

A hardness survey was made over these two specimens, the results of which are shown in Fig. 7. Though there are some differences observable at various points, the general hardness distributions are similar in both specimens, and there are no flaws visible in either section.

There remains the possibility of an error in the readings taken during testing (e.g. speed read as 710 r.p.m. instead of 690 r.p.m.) which could account for this difference.

CONCLUSIONS

1. The impact-torsion test does not reveal any difference in strength not shown by ordinary static tests on the particular steels used in this series.

2. Impact-torsion tests of welds with static strength up to 70 lb.-ft. in torsion can be made satisfactorily, provided care is taken in aligning the specimens on the axis of the testing machine.

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